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Section 1.1: Keynote Speakers

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Future cements

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Keywords: Cement, Concrete, Future Binders, Sustainability

Practical solutions for reducing CO_2 emissions from future production of cementitious materials are presented. In particular LC3 - Low Carbon Cement will be presented, a radical new technology which can reduce emissions by up to 40% compared to existing solutions. This technology has a global potential to reduce emissions by more than 10 times the emissions of the whole of Switzerland.

Given the climate emergency the world is facing, it is important to implement all means of reducing CO_2 emissions as fast as possible. Cement and concrete are often "demonised" due to the fact that they are responsible for some 7-8% of man-made CO_2 emissions. However, they are materials with lower environmental impact than all practical alternatives and this high amount of CO_2 is due to the enormous quantities produced: 4 billion tons of cement, used in some 40 billion tons of cementitious materials which is more than half of everything we produce.

Nevertheless, there are still many ways in which the environmental impact of cement and concrete can be further reduced. In considering these, it is important to recognize solutions, which are practical and can be applied in emerging and developing countries, where more than 90% is cement. In addition, it is important to work through the value chain, at the level of cement, the level of concrete and the level of structures. If solutions available today were implemented to their full extent, it is estimated that reductions of up to 80% could be possible

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Development of sustainable building materials with the guidance of nanoscience and nanotechnology

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Keywords: Nanoscience, Nanotechnology, building materials, sustainable, concrete.

Nanoscience studies the nature and characteristics of materials at the atomic and molecular scales; nanotechnology is a method of assembling, modulating, and modifying the structure of materials at the nanoscale, leading to the modulation of macroscopic properties. In recent years, the application of nanoscience and nanotechnology in sustainable building materials research has also developed rapidly. This report introduces the research progress of our team from two aspects. In terms of nanoscience, this report focuses on the application of first-principle and molecular dynamics simulations to study the changing law of the hydration process of tricalcium silicate, an important component of cement, at the atomic and molecular scales. First-principle calculations reveal that the mechanism of water adsorption on the surface of tricalcium silicate is mainly due to the transfer of electrons from the valence band maximum of the tricalcium silicate surface to the lowest vacant orbitals of the water molecules, which raises the Fermi energy level and moves the bonded molecular orbitals downward. Water adsorption, proton exchange and diffusion of water to the surface layer gradually accelerate the leaching of calcium ions from the surface. Calculations show that the energy barrier across which calcium ion precipitation occurs is not very high and is relatively easy to achieve. Calcium ion precipitation leads to the formation of two calcium silicate water complexes, laying the foundation for the formation of hydrated calcium silicate. The study provides a guidance for design the sustainable building materials at nano scale.

Chloride (Cl) induced steel corrosion is a major cause of durability issues of reinforced concrete (RC) structures and causes a large economic loss every year. Understanding the mechanisms of Cl induced steel corrosion in concrete is of great importance to develop the anti-corrosion methods and further lower down the repair and strengthening consumptions for sustainable development. Here, we investigate the mechanisms of steel depassivation and corrosion at atomic scale through the density functional theory (DFT) calculations. Our results reveal that Cl species can interact with the passive films through weakening the bonding of oxygen (O) with outer iron (Fe) atoms while enhancing the hybridization of O with inner Fe atoms, thus inducing the breakdown of passive films.

In terms of nanotechnology, this report describes how cement particles can be used to prepare 5 nm calcium hydroxide particles and to enhance the mechanical properties of organic materials, as well as to develop applications for related products. In addition, it also introduces how to use nanoparticles to modulate the nanostructure of cementitious materials to achieve the enhancement of macroscopic properties. These include the use of networks generated by the polymerization of organic monomers during hydration to improve the flexural strength of cementitious materials, the use of nano-silica to produce high modulus concrete, and the use of nano-foam to prepare high-quality lightweight cementitious materials. The report concludes with an outlook on the application of nanoscience and technology in civil engineering materials research to achieve sustainable development.

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Stone in historic buildings: challenges and opportunities for reuse and conservation

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Keywords: Natural stone, brick, building envelope, salt, monitoring

As we face major challenges like climate change and strong urbanization, historic buildings more than ever play a pivotal role in the urban fabric and the construction sector. Historic building envelopes suffer from climate stressors and environmental pressures like air pollution; energy efficiency and comfort of historic homes and commercial buildings are not meeting modern standards, and historic infrastructure is under threat from rapid urbanization. Nevertheless, they remain vital resources for the future, embodying a significant amount of carbon, (urban) history and an important spirit of place for people. Building conservation, adaptive reuse of buildings and circular reuse of building materials contribute to sustainable land use, consumption and production practices, and a reduction of greenhouse gas emissions, but they require profound understanding of the building materials.

Historic materials in the building envelope are essentially different from their modern equivalents in two specific ways: (i) they are not standardized or tested, (ii) they have long faced environmental exposure and sometimes treatments which have altered their properties. In addition, traditional construction techniques are often different to moderns, affecting structural and hygrothermal properties and energy efficiency. In this contribution we have a look at the conservation and reuse of traditional buildings materials like natural stone, brick and lime mortar. While natural stone is a natural product with often defined tolerances, a strong control on brick production leads to more homogenized properties. There is a big discrepancy between both products, with natural stone being prescribed to testing every few years, whilst brick is often sampled per production batch. When compared to historic materials, we observe a tendency for reducing porosity and water absorption, in tandem with increasing strength. As a result, knowledge and appreciation of traditional materials, which are often more porous and water buffering, is getting lost. We illustrate this with cases on the conservation of, inter alia, Maastricht limestone, a soft limestone with 50% porosity, used in the Limburg region (southeastern Netherlands, northeastern Belgium), and historical bricks in northern Belgium, whose properties are much more variable than modern ones.

In addition, their long-term exposure in the building envelope leads to non-linear changes in the material properties, the nature of which changes over time. This cumulative change is also known as the memory-effect. We demonstrate this with examples of natural stone weathering and brick decay, and possible action for in-situ conservation or for circular reuse. We illustrate how condition assessment is too often a snapshot on which major decisions are based and advocate for a transition towards a more preventive scenario with emphasis on longer-term monitoring of the building envelope. Special attention is given to on-site and non- to micro-destructive methods for condition assessment, and the processes of freeze-thaw action and salt crystallization. With this, we illustrate the specific challenges for the conservation and reuse of stone, brick and mortar in historic buildings, and the role of conservation as a science that is informed by multiple disciplines.

Chemical Admixtures – Essential for Successful Transition to "Green" Binders

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In light of global decarbonization efforts, the cement industry is facing fundamental changes in their current processes and technology. The two principal options for decarbonization are: (1) clinker substitution with reactive SCMs; and (2) carbon capture & utilization or storage (CCUS). Globally, both ways are explored and developed, with a majority of countries preferring clinker substitution. In this approach, not only the traditional SCMs (fly ash and GGBS), but other materials such as calcined clays, bottom ashes from incineration plants, activated lithium waste, red mud, coal gangue and biochar are looked at. Owed to their quite diverse surface chemistry and charge as compared to OPC, modified and tailored admixtures are required to achieve satisfying effectiveness. For example, in calcined clay blended cements (esp. those with high meta kaolin content) common slump retaining PCE polymers do not work as required. The reasons for the disfunction will be explained as well as the modifications which produce highly effective slump retainers even at clinker substitution rates of up to 80%. Similarly, in cements holding high contents of slag or other geopolymers, activators including NaOH, Na_2SiO_3, Na_2CO_3 etc. need to be applied to achieve sufficient early strength. Yet, common PCEs agglomerate and become ineffective at higher activator doses. Again, specific PCE structures and non-PCE polymers have been developed to achieve high fluidity and workability retention. Similar challenges exist for the other SCMs like biochar, red mud, mine tailings etc. It has been recognized that such broader variety of cement components requires a much more diverse portfolio of admixtures, as compared to OPC dominated cements. Furthermore, as many of these SCMs result in lower early strength, specific accelerators including C-S-H–PCE seeds, nano Portlandite, nano ettringite and amines will need to be applied.
It is concluded that a successful transition to green binders is highly dependent on the availability of novel admixtures well adapted to those specific binders.

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Prospect for Steel Slag (BOF) as Building Material

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Keywords: Fossil-free steel production, Slag mineralogy, Hydration products, Leaching, EU-legislation.

Steel industry worldwide nowadays produces 250 Mton of black steel slags that largely are not finding sustainable applications unlike their counterparts from ironmaking, the 350 Mton of white, Blast Furnace slags (GBFS), which are a raw material coveted by cement producers. The reasons for the disparity are multifold ranging from lack of clarity in the materials definition of steel slags, their inhomogeneity, a poor predictability of their performance in reuse, and limitations from environmental legislation. While a society without steel is inconceivable since the iron-age, and considering that the impact of steel making on our planet is untenable, a holistic vision on sustainable steel production is asked for.

The demand for steel worldwide is expected to rise with increasing world population, and even more so with increasing world prosperity. As a consequence, the global existing inventory of steel is insufficient to meet demand by recycling of scrapped steel, and substantial amounts of virgin Fe-metal still will need to be produced from iron-ores. The CO_2-emission in the established carbothermic method of iron production from iron-ore are associated with the dual function of carbon in this process, both as reductant and as source of heat. Those CO_2 emissions can be mitigated by using hydrogen as reductant (or more realistically methane) combined with electric heating. Currently, steel industry in Europe is transforming to less CO_2-intensive productions methods, and by 2030 it is projected that half of Europe's Blast Furnaces (BF) will become decommissioned.

Inevitably so-called carbon-steel making includes purification of crude iron metal at mildly oxidizing conditions leading to Fe-oxide losses to co-produced black steel slag. In the one stage fossil-free Electric Arc Furnace (EAF) process, solid state CH_4/H_2 reduced iron ores (DRI) are molten en purified, leading to a black ferrous slag containing all rock impurities as well as lime and dolime fluxes, incorporating oxidizable metals (V, Cr, Mo, Mn) as well as P, Si in oxide form. Alternatively, in two stage fossil-free processing, Reducing Electric Furnace (REF) conditions are applied, leading to a white slag, but impurities still must be refined in a next stage, again under mildly oxidizing conditions with the formation of a black slag, the same as in the current Basic Oxygen Furnace process. Thus in all process routes, the current BF-BOF, and the future DRI-EAF or DRI-REF-BOF route, together with purified steel, an iron-oxide bearing Ca-silicate slag is formed containing various amounts of Mn, P, V, Cr and other oxidizable elements. Thus, while CO_2-emissions can be curbed in future processes, and white slags will remain desired as SCM, the black slags concentrating all non-volatile oxidizable elements pose the real problem. To make steel production truly sustainable, inevitably the co-produced black slags need to find useful (value-added) applications. What are the prospects for these slags?

To develop the full potential of these black slags, reliable slag product specification need to be provided by producers from careful monitoring of their production. Accumulation of slag batches from the furnaces, mingling batches during subsequent handling for metal recovery and sieving into size fractions, results in a product of rather constant mineralogical and chemical composition, albeit at the individual fragment size still highly heterogeneous. Production of slags in restricted mineralogical categories can be attempted with pre-sorting of individual batches on e.g., free-lime content as done for BOF-slags at Tata Steel Netherlands. Very few steel companies have a slag quality monitoring system in place, and commonly even blending of back slags with slags from secondary (alloying) metallurgy is practice to arrive at one product for market-outlet. The indiscriminate connotation of all different slags from steelmaking, blended or not, with one generic term as steel slag has seriously compromised many studies on slag properties and applications. For one, BOF and EAF slags are distinctly different in their mineralogy but blending these with Ca-aluminate

slags from secondary metallurgy, i.e., Ladle (Furnace) slags, yields a product with very different properties. Researchers are advised only to work with a slag from a single defined process step, preferably obtained by mingling/averaging many production batches for representativity.

Studying quality controlled BOF slags, it will be apparent that their primary mineralogy is rather simple and comprised of only three major phases, C2S polymorphs, C4AF and wustite, normally with minor free-lime and occasional C3S. Still at elevated temperatures during solidification, additional phases CSF-perovskite and magnetite can form by oxidation. Next, during low temperature weathering, either passively by outdoor exposure or actively by forced steam curing, a set of secondary phases forms: portlandite (CH), Ca-carbonates (Cc), and amorphous CSH. The mineralogy of BOF slags is rather constant because of the limited range in main components with CaO/SiO2 = ~3 and Fe-oxide content (20-30wt%), in contrast to EAF slags with a wide range in CaO/SiO_2 of 1.3-2.8 and Fe-oxide content of 20-50wt%. The EAF slags have a more diverse mineralogy dominated by wustite and a range of silicates, from C2S – C7MS4 – C3MS2 to CfS, melilite with minor spinel phases and C4AF. Water-quenching of EAF slags of low Ca/SiO_2 can lead to extensive glass formation, but process equilibria rule out that EAF slags crystallize free-lime. Additional phases reported in BOF or EAF slags, like C3A (or its hydrate, katoite), C12A7, γ-C2S indicate blending with ladle slags from secondary metallurgical processing.

BOF slag mineralogy shows similarity to Ordinary Portland Cement (OPC) and finely milled slag can be hydrated or carbonated to form a binder. The hydration products of BOF slag are ferrous-forms of hydrogarnets and hydrotalcite, portlandite and CSH-phase. To achieve good strength, low water to slag ratios (W/B) are favorable, since only limited amounts of water become bound in the hydration products and excess water leads to increased porosity. There is some controversy whether BOF slags can be partially amorphous. The primary solidified slag is fully crystalline, but extensive milling to cement-fineness appears to induce some amorphization, largely at the expense of C2S, as shown in Rietveld-XRD analyses. In addition, CSH formed by weathering of primary slag is present as amorphous substance. During hydration of slag powders, the product phases are only partially crystalline and amorphous content can rise to 30wt% with advanced hydration. The formation of portlandite indicates that BOF slag possesses hydraulic properties like OPC. Relative contribution of primary phases in the early on hydration (first weeks) are dominated by C4AF with less C2S, but at later ages it is reversed. Wustite contributes in small amounts. Reactions can be stimulated with additives, and adequate strength can be obtained for mortars containing 100% BOF-slag powder as binder.

BOF slag in blends with OPC can give rise to delayed setting, a feature also observed in stand-alone BOF slag binders. There is no consensus on how the interaction of pore fluid – solid phase controls the delayed setting. The relevance of the problem stays limited as long as the current EU-standard excludes incorporation of black slags in cement.

BOF slags, on average being higher than EAF slags in potentially harmful metals (V, Cr, Mn), show good retention properties, also after hydration, as long as fluid phase pH-values stay high (pH~12.5) during leaching and buffered by the mineral assemblage C2S – CH – CSH. Release of Cr is accompanied by Al in leachates, and V appears coupled to silica. With carbonation of slag the leaching of V drastically increases. Carbonation associated with ageing of slag-based binders increases V-release but this can be mitigated by choosing the right type of additive. Nonetheless, the presence of environmentally sensitive metals in black slags remains a serious threat for their application in building materials. Explicit legislative limits on leaching or on content of V, Cr, Mo, etc restrict the otherwise positive prospect for their use in building products. If EU and member state legislation remains restrictive, black slag recycling can only be accomplished with costly advanced hydro- or pyrometallurgical treatment.

Exploration of cement-based biomimetic metamaterials

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Keywords: Cement-based, Biomimetic metamaterials, functional.

China holds a leading position globally in terms of the scale and number of major engineering and construction projects, cement-based concrete is a fundamental material for national major engineering projects, enhancements in the quality and performance are critical supports for innovation in major engineering structural systems as well as for ensuring their safety and durability. Extraordinary demands on the performance of construction materials require early layout to win future infrastructure competition, it is important to accelerate the update and iteration of traditional construction materials and, leading to disruptive leaps in their mechanical properties, durability, and functionality.

Cement-based biomimetic metamaterials are inspired by certain structural characteristics or functional properties of biological organisms. This process achieves significant enhancements in mechanical properties and introduces new functionalities such as super-insulation, super-hydrophobicity, self-healing, and self-sensing. These advanced properties make these materials highly suitable for diverse applications including energy projects, defence engineering, extreme environments, and cutting-edge sectors. In this report, the biomimetic superhydrophobic concrete, biomimetic high strength and toughness concrete, cement-based biomimetic aerogel/hydrogel, cement-based biomimetic photothermal metamaterials, cement-based self-cooling fabric, cement-based battery and thermoelectric materials which are invented by our research group. Advanced metamaterials help build low-carbon, smart, and resilient cities of the future.

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Bio-based materials for decarbonising the building sector

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Keywords: Decarbonation, Carbonation, insulation, fibres, treatment.

Decarbonizing the building sector is critical to lowering emissions across all of society, as buildings generate about 37% of total global energy-related CO_2 emissions. In response to the urgent need for climate action, bio-based materials are emerging as a promising solution for decarbonising this sector. Derived from renewable biological sources such as plants, agricultural waste, or microorganisms, bio-based materials offer low embodied carbon, potential for carbon sequestration, and enhanced sustainability throughout their life cycles.

Key bio-based materials include timber, bamboo, hempcrete, mycelium composites, straw bales, and cellulose insulation. These materials not only have significantly lower production emissions compared to their synthetic or mineral-based counterparts but also often act as carbon sinks by storing atmospheric CO_2 absorbed during biomass growth. In addition to their environmental benefits, bio-based materials can offer improved indoor air quality, thermal insulation, and energy efficiency. Their integration into modern construction aligns with circular economy principles, encouraging recycling, biodegradability, and local resource utilization. However, challenges remain, including durability, standardization, fire, and market acceptance. Overcoming these barriers will require supportive policies, investment in research and innovation, and industry-wide collaboration.

Depending on the amount of biomass integrated into a material, this can mechanically reduce its total CO_2 emissions. In some cases, this carbon storage can partly or even fully offset the emissions related to the material's production phase. This is the case, for example, with hempcrete, which stores more CO_2 than is emitted during its production. The carbon storage capacity of bio-based materials can thus be accounted for in the life cycle assessment of buildings when using the so-called dynamic methodology. This method includes an analysis of impacts over time.

In conclusion, bio-based materials hold transformative potential for decarbonising the building sector. By leveraging their ecological and performance advantages, the construction industry can move towards a more sustainable, low-carbon future, in line with global climate targets and green building practices.

How Durable are Carbon Mineralized Construction Materials and Products

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Keywords: Carbon mineralization, Subsequent hydration of cement, Chloride binding and transportation, Weathering carbonation, Corrosion of steel

The carbon mineralization in cement-based materials has been widely recognized as one of the most promising technologies for CO_2 utilization and storage, but the long-term durability of CO_2 mineralized materials and products requires attention. Usually, less than 50% cement in the CO_2 mineralized materials and products is carbonated during the early-stage carbon mineralization. The remained uncarbonated cement clinker will hydrate when the CO_2 mineralized materials and products are exposed to moisture environments. The subsequent hydration and microstructural evolution of these materials, with reactions occurring between $Ca(OH)_2$ and $SiO_2 \cdot H_2O$, facilitate pH recovery, densification of microstructure and sustained strength development and in CO_2 mineralized materials and products. CO_2 mineralization reduces the chloride binding capacity of these materials, but enhances their resistance to rebar corrosion due to a significant decrease in chloride diffusivity. Conversely, CO_2 mineralization also lowers the carbonation coefficients of the materials. Thus, CO_2 mineralization appears to be a promising approach for carbon mineralization, good quality construction materials and products, and even mitigating chloride-induced reinforcement corrosion of steel reinforced construction products.

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Microstructural modelling: From alite hydration to ITZ of blended cements

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Keywords: Microstructural modelling, cement hydration, ITZ, vector approach

The development of microstructural models to simulate the development of hydrating cement phases started in mind-90s. Most of these models focused on either single phases or ordinary Portland cements, with limited work on blended cements. A significant part of the microstructural modelling work demonstrated that the simulated microstructures had significant differences from real cements. Still, these models have been able to provide important information that has improved the understanding of cement hydration, microstructural development and the development of various performance parameters of cement paste. Recently, there has only been limited work on the development of microstructural models with only a few research groups continuing the work. The arrival of artificial intelligence (AI)-based approaches have led to the development of newer approaches to considering the microstructure. Vector-based microstructural models can still play an important role in improving our understanding of the more complex cementitious systems being used today.

In this study, the flexible vector modelling approach using the microstructural modelling platform μic has been used to model first some simple systems like alite and Portland cement and then more complex blended cements like limestone calcined clay cement (LC^3). It has been shown how the overall implications of particle-level mechanisms can be easily simulated using these models. The models are able to capture the kinetics and phase assemblages as hydration continues. The computational volumes extracted from these models have also been successfully used to model the development of mechanical properties like elastic modulus, creep, etc. The simulated pore-structures were, however, found to be much coarser than real cements, indicating that any property that is influenced by the pore-structure cannot be correctly represented by these models. It was seen that although it is important to include realistic particle size distributions Still, it was possible to model complex phenomena like autogenous shrinkage through the use of correction factors.

Moving from ordinary Portland cement (OPC) to blended cements required the introduction of reactive phases, such as fly ash, whose hydration is not as well-understood. The wider particle size distribution of the supplementary cementitious materials (SCMs) necessitated the use of more powerful computational approaches, which are inherently included in μic and can handle a larger number of particles. The results showed that the application of concepts understood for the hydration of clinker particles can also be applied to blended cements and SCMs. However, data on the reaction of the SCMs and their hydration products is important. Once this data is available, the model can not only be used to simulate the microstructure of hydrating blended cements, but also the variations in engineering properties due to changes in the SCMs. Expansion of these models to multi-SCM composite cements like LC^3 further demonstrates the necessity for data that can be difficult to obtain for such complex systems.

The models were further extended to mortars, where, unlike earlier models where a simple barrier was introduced to simulate the filler effect, sand particles were inserted into the system. Once again, the flexible and powerful computational tools that are available in μic allowed the Interfacial transition zone (ITZ) to be modelled explicitly in the computational volume. An analysis of the ITZ shows that the model can provide insights into the gradients of properties in this zone. More importantly, the influence of particle size distribution and the reactions of SCMs is better understood through the models. The influence of shape of particles is also understood. It was found that the strengthening of the ITZ holds the key to the

good strength and improved transport properties of mortars containing SCMs despite their limited reactivity.

Overall, it is seen that despite the differences between the simulated microstructures and real cements, the models can be used to obtain useful information and knowledge about cement, as long as the simplifications and limitations of the models are understood.

Carbonated RCP as SCMs: Reaction Mechanisms and Scale-Up

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Keywords: Enforced Carbonation, Circular Economy, Recycling, Supplementary Cementitious Material

The enforced carbonation of recycled concrete paste (RCP) presents a triple opportunity for CO_2 sequestration combined with the production of reactive supplementary cementitious materials (SCMs) and integration of circular economy principles into cement production by turning waste into a high-quality product. This process transforms hydrated cement phases into stable carbonates and pozzolanic alumina-silica gel (Al-Si gel). This talk focuses on the mechanistic understanding of the carbonation reactions and their implications for composite cement hydration and performance.

Enforced carbonation replicates natural carbonation under accelerated, controlled conditions (10–90 °C, atmospheric pressure, elevated CO_2 concentration), targeting calcium-rich hydrates such as portlandite, calcium silicate hydrate (C-S-H), and calcium aluminate hydrates. Extensive scientific studies have elucidated the reaction mechanisms underpinning enforced carbonation, enabling its application at industrial scale. The reactions proceed via a three-step mechanism: (1) dissolution of Ca^{2+} and other ions from the solid phase, (2) dissolution of CO_2 into the aqueous phase forming carbonate species (CO_3^{2-}, HCO_3^-), and (3) precipitation of $CaCO_3$ and Al-Si gel. Although macroscopically gas-solid, the process is governed by nanoscale gas-liquid-solid interactions facilitated by thin films of water adsorbed on solid surfaces. The carbonation of RCP is rapid, typically completing within minutes for particles <100 μm. The resulting $CaCO_3$ predominantly crystallizes as calcite, while the Al-Si gel forms a highly polymerized network with Q^3–Q^4 silicate species and tetrahedrally coordinated AlO_4^- units. The Al/Si ratio of the gel depends on the original cement composition and influences its pozzolanic reactivity. The gel's high surface area (>200 m^2/g) and nano-porosity contribute to its rapid dissolution and reactivity in cementitious systems.

Carbonated recycled cement paste (cRCP) can serve as a reactive supplementary cementitious material (SCM) in both binary and ternary composite cements. In binary systems with Portland clinker, the Al-Si gel in cRCP reacts with portlandite and calcium carbonate ($CaCO_3$), forming additional calcium silicate hydrate (C-S-H) and monocarbonate phases. This reaction enhances early strength development and refines the pore structure. The rapid reaction of the gel leads to the formation of a calcium-alumino-silicate hydrate (C-(A)-S-H) phase with a low calcium-to-silicon (Ca/Si) ratio, compared to traditional Portland cement systems. Over the first 7 days, belite and residual alite continue to react, increasing the Ca/Si ratio of the C-(A)-S-H phase to levels typical of blended cements. After this period, further microstructural development is primarily driven by clinker hydration and the activity of other SCMs. The high reactivity of cRCP makes it suitable for combination with slower-reacting SCMs, such as calcined clay, in ternary blends. These systems benefit from sequential hydration: clinker phases react first, followed by the Al-Si gel, and finally the secondary SCM. This sequence minimizes adverse interactions between pozzolanic materials and enables clinker content to be reduced to below 50%. Experimental studies have shown that cements containing 20–40% cRCP exhibit mechanical performance comparable to, or better than, conventional cements incorporating slag or fly ash, particularly at early stages of hydration. The effectiveness of cRCP depends on the degree of carbonation and the purity of the recycled paste. High carbonation ensures complete transformation of C-(A)-S-H into a reactive gel, while selective separation enhances the cement paste content. Industrial-scale trials have confirmed the

feasibility of this technology, demonstrating that cRCP-based cements can be produced and used without requiring modifications to existing concrete production processes.

Development of low-carbon and high-performance lightweight concrete

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Keywords: Low-carbon lightweight concrete; Lightweight aggregates; CO_2 foam concrete; Carbon reduction; Durability

Modular Integrated Construction (MiC) is gaining increasing importance in Hong Kong. However, concrete MiC manufacturers and users suffer from low assembly efficiency and lifting difficulties due to the use of conventional normal-weight concrete. Traditional lightweight concrete is typically limited to being used as non-load-bearing elements. Therefore, developing high-performance lightweight concrete (HPLC) capable of carrying structural loads is essential. Hong Kong PolyU has developed a low-carbon HPLC to fulfil the structural requirements of MiC and successfully applied this technology to a MiC project in Hong Kong. The adoption of supplementary cementitious materials to replace cement and high-strength lightweight aggregates contributes to reducing the embodied carbon of the HPLC. Incorporating lightweight materials into sustainable ultra-high-performance concrete (UHPC) can produce durable HPLC, characterised by low density, ultra-high strength, and superior durability. The utilisation of waste glass in the form of powder and cullet enabled the production of a desirable UHPC binder for HPLC. In addition to the strong binder, HPLC has to be produced using either sintered lightweight aggregates or high-strength cold-bonded synthetic aggregates. Combining waste glass powder with other solid wastes, such as incinerated sewage sludge ash, can lower the sintering temperature and produce high-strength, sintered, lightweight aggregates with a fine pore structure. Inspired by the cross-sectional microstructure of bamboo, a core-shell lightweight structure comprising a lightweight core and a strong cementitious shell is used to fabricate cold-bonded core-shell lightweight aggregates. Carbon nanotubes (CNTs) are also used to effectively reinforce the strength and modulus of the core-shell lightweight aggregates. Apart from the structural grade HPLC, we have also developed foamed concrete incorporating waste CO_2 in the foaming process. CO_2-foamed concrete can be used as non-structural walls, offering good strength and excellent thermal insulation properties. Furthermore, a superhydrophobic pore structure has been designed to enhance the durability of CO_2-foamed concrete.

Active Rheology Control of Cementitious Materials

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Currently, processing of concrete does not take full profit of the rheological potential. It is still largely labour-driven and sensitive to the human factor and environmental conditions. Fresh concrete regularly shows placement problems such as blocking during pumping or leaking of formworks. Practitioners can only passively rely on the concrete rheology, without any practical option to intervene post-mixing. Within the ERC Advanced Grant Project 'SmartCast', a new concept has been developed of actively controlling the rheology of fresh concrete during casting operations by incorporating specially designed responsive components. These newly developed electro-responsive superplasticizers or magneto-responsive additions can be manipulated by an external electromagnetic trigger signal. This results in real-time changes to the rheological behaviour of the cementitious material. The main advantage of this Active Rheology Control (ARC) technology is that it allows the user to intervene actively after mixing of the cementitious material, enhancing the target property. This newly gained agility can contribute to increased processing speed and placement reliability in case of traditional casting methods but can also facilitate advanced 3D concrete printing.

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The potential role of SMACs in the future global cement scenario

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Keywords: Synthesis, cement, hydration, pozzolan, activation

The fundamental objective of the 5C strategy (CEMBUREAU plan of decarbonization for the cement industry) is to arbitrate a set of actions on each of the key elements constituting the value chain of the construction's life cycle; it means to rationalize carbon footprint from the initial stage of the Clinker production in cement factories till the final stage of recycling the demolition waste (passing through all intermediate stages). At the time of its publication, the 5C strategy sounded like a solidly structured plan, but time has revealed the existence of some weaknesses in the core of this plan. Do Europe need a plan "B" for facing the decarbonation of the cement industry by 2050?

SMACs (Synthetic Multi Action Commodities) are materials with high potential to contribute to establish a decarbonization plan "B" for the cement industry. The main characteristics of SMACs are:

√ Worldwide available raw materials for synthesis (compatible with the Circular Economy)

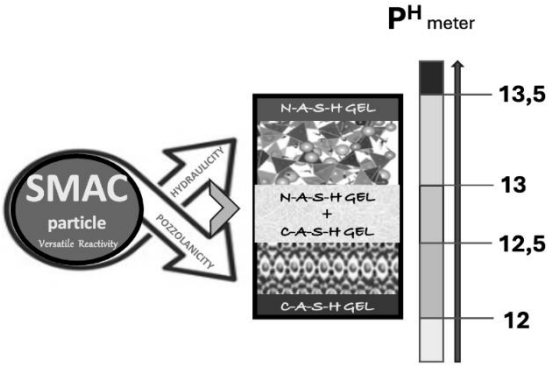
√ Moderate temperature of synthesis (less than 1100°C)

√ Low calcium content (low CO_2 footprint)

√ High percentage of glassy phase

√ Easy adaptation to current regulations

√ High potential to develop *extra properties* beyond those strictly related to civil engineering



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Advantages of Medium pH Concrete in a Sustainability Perspective

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Keywords: Alternative reinforcement, Aggregate, Concrete, Pozzolana, Sustainability.

The production of cement word-wide stands for about 8% of all anthropogenic CO_2 emission. The simplest and most cost-efficient way to reduce the emissions is to replace clinker in blended cements, or cement in concrete mixes, by a supplementary cementitious material (SCM) with substantially less CO_2 emission than the cement clinker. This has been done in the later years with modest replacement ratios to typically 25% (e.g. fly ash with some limestone) except for blast furnace slag allowing up to 95% in the European standard. However, fly ash will be obsolete due to shutting down of coal fired energy plants and changes to the iron production process will be made so there will be no more blast furnace slag available, all for the sake of reducing CO_2-emissions and limiting global warming. Hence, there is a search for alternative SCMs, and calcined, natural clays is an alternative with great potential worldwide. However, these are pozzolanic materials consuming calcium hydroxide from the cement hydration. Replacing cement in concrete with the highest possible amount (>50%) of pozzolana to maximize reduction in CO_2 emission while maintaining concrete properties sufficient for construction, consumes all calcium hydroxide and reduces pH to a level (< 10) that no longer colour common indicators like phenolphthalein or thymolphthalein. This means that steel rebars no longer are in the passive pH range and protected against corrosion as in regular concrete with pH > 13. On the other hand, this opens up for alternative reinforcement that are non-corrosive in a medium pH-range (6-9), such as ordinary glass-fibres, FRP based on polyester binder and aluminium metal. Such non-corrosive reinforcement allows the use of the cheapest and most effective accelerator, calcium chloride, that will counteract some of the lower early strength due to high replacement of cement by slower reacting SCMs. In a resource perspective it allows the use of seawater as mixing water and sand dredged from the sea without washing, addressing limited fresh water and sand resources in many places. The medium pH (< 10) of such a concrete secures the stability of fibres and aggregate based on recycled glass, as well as allowing safe use of natural aggregates prone to expanding alkali-aggregate reactions (AAR) in regular concrete. Even aggregate separated from excavation masses can be utilized without checking for AAR vulnerability or need to remove occasional glass contamination. The removal of calcium hydroxide from the binder also leads to excellent sulphate resistance for such a concrete, as it is the first point of a sulphate attack. The use of a non-corrosive reinforcement also allows for reduced concrete cover and thereby reduced volume of concrete needed. Only sufficient concrete cover for mechanical grip of the reinforcement is required. Making a C35 concrete would serve about 80% of the concrete market from a strength perspective. In order to protect the regular steel reinforcement against corrosion caused by carbonation or chloride ingress, the water-to-cement ratio (w/c) is kept low to reduce porosity and thereby the strength becomes much higher than need for construction. Furthermore, low w/c is often obtained by using more cement relative to aggregate and a higher strength requires more reinforcement to minimize crack width to further protect the steel. Hence, medium pH concrete with non-corrosive reinforcement opens up for construction design based on the required strength, not durability concerns, as a concept for prolonged service life without maintenance and better resource utilization. Most of the reasons for maintenance and repair in modern concrete is due to corrosion of steel reinforcement caused by either carbonation or chloride ingress but one should remember that the concrete binder performs just fine when carbonated or having intruded chlorides. Thus, reinforcement steel is the real Achilles heal of modern reinforced concrete. All of the above features are discussed and examples given in the key-note lecture.

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Closing the Loop – Leveraging alternative SCM sources for future binder systems

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Keywords: Sustainable Construction, Secondary Raw Materials, Waste Valorization, Mineral Carbonation, Circular Economy

With an annual production exceeding 30 billion tons, **concrete** is the second most consumed material on Earth, surpassed only by water. This widespread use translates to an estimated three tonnes of concrete consumed per person globally each year, making it the most utilized man-made product worldwide. The increasing demand for housing and critical infrastructure to support a global population exceeding 8 billion necessitates the extraction of over 43 billion tons of **primary materials** from the Earth's crust annually. Simultaneously, more than 35 billion tons of waste are generated annually, encompassing vast amounts of industrial by-products such as red mud, mine tailings, slag, ash, and a significant volume of construction and demolition waste. A substantial portion of this waste currently ends up in landfills, posing considerable environmental and economic challenges.

A vast amount of primary raw materials can be conserved through the strategic utilization of these widely abundant **secondary raw material streams**. However, a significant obstacle lies in the inherent chemical complexity of these materials and the need for a more profound understanding of their physicochemical properties to effectively close material loops. This critical knowledge gap is our primary motivation for research aimed at better understanding the potential uses of these material streams, highlighting pathways for beneficiating them and transforming them into valuable construction materials for future applications. We will present three examples, based on ongoing projects, demonstrating the approaches taken.

Research explores different methodologies for valorizing waste streams, focusing on chemical activation and their integration into novel binder systems.

Red Mud Utilization

Firstly, we discuss the utilization of **red mud**, also known as bauxite residue. This by-product of alumina production is often classified as a hazardous component, leading to the annual deposition of over 4 billion tonnes of the material in landfills globally. Despite this, red mud contains highly relevant elements such as alkali earth metals, silica, iron oxide, and alumina oxide, making it an ideal candidate for valorization in the construction or building materials industry. Beneficiation approaches for bauxite residues demonstrate the potential to generate a reactive **supplementary cementitious material (SCM)** that can effectively substitute primary resources. Furthermore, it has been found that incorporating these beneficiated red muds into ternary blends with limestone can significantly improve the overall performance of the resulting concrete. Interestingly, studies have identified the formation of new reactive components, such as cancrinite, which exhibit pozzolanic properties. It was shown that **thermodynamic modeling** helps to further understand and optimize their contribution to material performance in terms of mechanical properties and durability.

Beneficiation of Steel Slags

Secondly, focus is placed on the beneficiation of **steel slags**. More than 300 million tonnes of steel slags (BOF - basic oxygen furnace, or EAF - electric arc furnace type slags) are generated annually during steel manufacturing, presenting a substantial waste management challenge and an opportunity for resource recovery. These slags often contain high amounts of calcium silicate and ferrite type phases. Research on beneficiated BOF slags shows that the silicates within these slags can be effectively activated through **mineral carbonation** approaches, thereby significantly enhancing their reactivity. Additionally, the hydration of ferrite phases contributes to further space filling within the binder matrix, improving material density and strength, which can be further activated by the use of chemical admixtures. Notably, hydration investigations of activated by-products of the steelmaking process have revealed the formation of "unusual" components such as siliceous hydrogarnet, which are not commonly observed in conventional cementitious systems, indicating unique reaction pathways.

CO_2 as a Raw Material Source

Finally, **CO_2 mineralization** pathways are explored. CO_2 should be seen as a potential "raw material source" within the construction industry. CO_2 mineralization approaches offer promising paths to activate non- or low-reactive material streams, including steel slags and recycled concrete fines. Moreover, it enables the production of entirely new clinker-free binder systems that solely harden through carbonation. While the concept holds immense potential, optimizing process conditions remains a key challenge. A specific example of such a binder system, developed based on BOF steel slag, will be discussed, demonstrating the feasibility of potentially creating CO_2-negative binders based on currently valid environmental assessment schemes. Hence, such cementitious systems not only utilize industrial waste but also sequester carbon dioxide, offering a dual environmental benefit.

Conclusion

In conclusion, a vast and largely untapped reservoir of secondary resources is available on our planet. It is our common responsibility to prioritize the valorization of these materials before continuing to consume valuable primary resources at an unsustainable rate. By pursuing environmentally sensitive beneficiation approaches and integration of secondary raw material streams into the construction value chain, we can achieve a significant step towards realizing climate- and resource-neutral construction practices. This transition is imperative for present and future sustainable construction measures.

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Volume 1

Section 1.2: Bio-based Building Materials

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Additive manufacturing of intelligent modular components from bio-based industrial waste

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Keywords: bio-based materials, circularity, additive manufacturing, construction, functionalization

BIOGEMSE project aims to pioneer a transformative approach in modern architecture by developing bio-intelligent, sustainable, circular, and safe modular construction products. The project is structured around three interconnected research fields: (i) the development of circular and bio-based materials tailored for Additive Manufacturing (AM), (ii) the integration of biologically inspired processes through flexible and robotised AM technologies, and (iii) the realisation of manufacturing-enabled bio-intelligent product functionalities.

AIMEN will fine-tune eco-friendly mortars derived from industrial bio-waste to suit AM processes, replacing conventional fossil-based construction materials. Generative AI tools will be employed to explore and design bio-mimetic structures, leveraging nature-inspired functionalities. AM technologies will be enhanced at both hardware and software levels to meet the customization and performance needs of the built environment.

The project introduces a sustainability-by-design (SSbD) framework to evaluate environmental impacts, circularity, and safety. Bio-based additives such as TiO_2, biochar, and PCMs will be investigated to confer functionalities like thermal insulation, CO_2 capture, self-cleaning, and pollutant degradation. In parallel, material processing parameters—rheology, setting times, and mechanical strength—will be optimized for compatibility with 3D printing systems, including the upscaling of these printable bio-materials.

To validate the approach, bio-intelligent modular components will be deployed in three Smart Living Labs under diverse climatic and functional conditions, aiming to demonstrate performance, foster scalability, and support future EU-wide implementation.

Advancing Carbon Accounting for Engineered Wood Products and Timber Buildings: Insights, Challenges, and Opportunities for Decarbonised Construction

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Keywords: Carbon accounting, Engineered wood product, Timber building, Carbon footprint, Sustainable construction

The construction sector is a major contributor to global carbon emissions, necessitating a shift towards sustainable building materials. Engineered wood products have gained attention as low-carbon alternatives to conventional materials such as steel and concrete. However, quantifying their carbon footprint remains complex due to variations in production processes, life cycle assessment methodologies, and biogenic carbon accounting approaches. This systematic review synthesises existing studies on the carbon footprint of engineered wood products and wooden buildings, with a specific focus on the production stage, covering raw material extraction, processing, and manufacturing.

A total of 63 peer-reviewed articles and reports were analysed, capturing data on key parameters, including author, year, geographical location, functional unit, life cycle inventory database, type of panel product, system boundary definitions, inclusion of biogenic carbon stock, and dynamic carbon accounting factors. This study systematically analysed carbon accounting methodologies - Life Cycle Assessment, Material Flow Analysis, and IPCC guidelines - with a focus on EWPs during the production stage. Results reveal significant variability in carbon footprints, ranging from -40 to 1050 kg CO_2eq m^{-2} for timber buildings and 12 to 759 kg CO_2eq m^{-3} for EWPs, largely influenced by regional forestry practices, supply chain dynamics, and methodological differences. Cradle-to-Gate boundaries dominated EWP assessments (53%), while Cradle-to-Grave frameworks were prevalent in building studies (43%).

The review highlights significant variations in reported carbon footprints across different studies, influenced by regional differences in forestry practices, energy sources, and manufacturing efficiencies. The choice of life cycle assessment methodology and system boundary definition plays a critical role in determining emission outcomes. Studies using cradle-to-gate assessments often report lower carbon footprints compared to those incorporating end-of-life scenarios. Additionally, the treatment of biogenic carbon remains inconsistent, with some studies adopting static accounting while others employ dynamic life cycle assessment to capture temporal variations in carbon sequestration and release.

Among engineered wood products, cross-laminated timber, glued laminated timber, laminated veneer lumber, and oriented strand board exhibit varying carbon footprints, largely dictated by differences in

adhesive use, processing intensity, and material efficiency. Hybrid cross-laminated timber products, integrating materials such as rock wool or plywood, present additional complexities in carbon accounting. Moreover, geographical disparities in energy grids impact carbon intensity, with European and North American production generally benefiting from lower-carbon electricity compared to regions relying heavily on fossil fuels.

This review identifies critical gaps in current literature, particularly the need for harmonised life cycle assessment methodologies that account for dynamic carbon flows and a standardised approach to biogenic carbon accounting. Future research should also explore the integration of region-specific carbon intensity factors and assess the implications of emerging decarbonisation policies on the engineered wood product industry. Additionally, greater transparency in life cycle assessment datasets and alignment with international carbon reporting frameworks, such as those outlined by the Intergovernmental Panel on Climate Change, can improve comparability across studies.

By consolidating current knowledge on the carbon footprint of engineered wood products during production, this review provides insights for policymakers, industry stakeholders, and researchers seeking to optimise material selection for low-carbon construction. Understanding these variations is crucial for ensuring that engineered wood products are accurately represented in carbon mitigation strategies and life cycle assessments of sustainable buildings.

Agricultural Waste Revalorization: Enhancing Concrete Durability and Circularity through Rice Husk Ash Optimization in Arid Climates

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Keywords: Agricultural waste valorization, Rice husk ash, Supplementary cementitious materials, Concrete durability, Life cycle assessment.

The construction industry is one of the largest consumers of raw materials and a major contributor to CO_2 emissions, particularly due to cement production. At the same time, agricultural waste such as rice husks is often burned in open fields, leading to air pollution and wasted resources. Rice husk ash (RHA), a byproduct of burning rice husks, contains a high amount of silica and can be used as a partial replacement for cement in concrete. This not only helps reduce waste but also lowers CO_2 emissions. However, the use of RHA in concrete is still limited due to inconsistent quality and a lack of research on its performance in hot, dry climates. This study focuses on improving the effectiveness of RHA as a cement replacement and testing its performance in concrete under conditions similar to arid regions. The goal is to develop a simple and repeatable method for using RHA in concrete to enhance its strength and durability while reducing its environmental impact.

Rice husks were collected from local farms in Egypt, washed, dried, and burned at 650°C for 2 hours to produce RHA. The ash was then ground into a fine powder using a ball mill. Four types of concrete were prepared: a control mix with 100% cement, and three mixes with 10%, 20%, and 30% of the cement replaced by RHA. All mixes had the same water-to-cement ratio of 0.45. The concrete samples were cured at 40°C to simulate hot, dry conditions. The compressive strength of the concrete was tested at 7, 28, and 56 days to evaluate its strength over time. Sulfate resistance was tested by soaking samples in a sulfate solution for 90 days and measuring weight loss and strength retention. Chloride permeability was assessed to determine how easily chloride ions could pass through the concrete. A simple life cycle assessment (LCA) was also conducted to compare the CO_2 emissions of RHA-concrete to regular concrete.

The RHA had a high silica content of 92%, making it suitable for replacing cement. The grinding process ensured the particles were small enough to mix well with cement. In terms of performance, the mix with 20% RHA (RHA20) showed the highest compressive strength at 28 days, reaching 48.2 MPa, which was 15% higher than the control mix at 41.9 MPa. The mix with 30% RHA (RHA30) had lower initial strength but matched the control by 56 days. The RHA20 mix also performed better in durability tests, losing only 12% of its weight in the sulfate test compared to 22% for the control mix, and showing lower chloride permeability, indicating better resistance to chemical damage. The environmental analysis revealed that using 20% RHA reduced CO_2 emissions by 18% compared to regular concrete. If all the rice husks in Egypt were used in this way, it could save up to 216,000 tons of CO_2 annually.

In conclusion, this study demonstrates that RHA can be an effective replacement for cement in concrete, particularly in hot, dry climates. A 20% replacement of cement with RHA improves the strength and durability of concrete while significantly reducing CO_2 emissions. The method is straightforward and can be implemented by a single researcher within a year. It is also scalable and applicable to other regions with similar agricultural waste and climate conditions. Future research could focus on testing RHA-concrete in real-world applications and exploring the use of other types of agricultural waste in construction materials.

Application of South African agricultural wastes as supplementary cementitious materials

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Keywords: Sugarcane bagasse ash, Corncob ash, Portland cement, Mortar, supplementary cementitious material.

In the pursuit of reducing greenhouse gas emissions, particularly within the construction industry, eco-friendly and renewable cement replacement materials are being explored. The primary contributor to carbon emissions in this sector is the manufacturing of Portland cement. Additionally, cement extenders aim to reduce costs, ensuring a viable construction industry for future demands with limited resources. Some studies have suggested use of agricultural waste such as sugarcane bagasse ash (SCBA) and corn cob ash (CCA) as cement extenders in concrete mixtures. SCBA is a byproducts of sugar refineries, where sugarcane bagasse is burned for heat generation during the refining process. Similarly, CCA is derived from the combustion of corn cobs, typically used for heat generation. This study explored the influence of sugarcane bagasse ash (SCBA) and corn cob ash (CCA), produced in South Africa, on the properties of mortar mixtures. Mortars were prepared with varying proportions of SCBA and CCA, ranging from 0% to 40% as cement extenders, while maintaining a constant water-to-cement ratio (w/c) of 0.45. Fresh mixtures were assessed for workability and setting time, and 50 mm cubes were cast for compressive strength testing at 7 and 28 days. Additionally, a microstructural analysis of hardened mortars was performed using scanning electron microscopy (SEM). The results indicated that the inclusion of CCA caused a notable reduction in the workability of fresh mixtures, whereas the impact of SCBA on workability was minimal. Similarly, CCA significantly reduced the compressive strength of mortars, while the strength loss associated with SCBA was considerably lower. Regarding setting time, SCBA and CCA demonstrated contrasting effects: increasing SCBA content led to prolonged setting times, whereas CCA reduced the setting time of the mixtures. At an optimal SCBA replacement level of 20%, the mortars achieved a 28-day compressive strength of 66 MPa, a workability value of 179 mm, and initial/final setting times of 213 minutes and 330 minutes, respectively.

Bamboo Bio-Concretes for Sustainable Construction: Mechanical Properties and Constitutive Modelling

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Keywords: Bamboo bio-concrete, Bio-aggregates, Compressive strength, Ductility, Sustainable construction

In recent years, there has been growing interest in the use of biomaterials in construction, particularly as the sector seeks to reduce its environmental impact. Bio-concretes, which incorporate plant-based aggregates, offer a promising alternative to traditional construction materials. While numerous studies have explored the use of fine bio-aggregates in bio-concretes, research on the use of larger bio-aggregates, particularly bamboo, is still limited. Most existing studies use cubically shaped bamboo particles, which are specifically produced for research purposes. In contrast, this study aims to investigate the mechanical performance of bamboo bio-concrete (BCB) using irregularly shaped bio-aggregates derived from bamboo waste generated by industries such as furniture manufacturing. This approach maximizes the use of available materials, reducing waste and promoting a circular economy. Bamboo is an ideal candidate for this application due to its rapid growth, widespread availability—particularly in countries like Brazil—and its excellent mechanical properties, including high tensile strength and flexibility.
The primary goal of this study was to evaluate the effect of varying bamboo bio-aggregate content on the mechanical properties of bio-concretes, specifically focusing on compressive strength, modulus of elasticity, and ductility. Understanding how these properties are influenced by bio-aggregate content is crucial for determining the viability of bamboo bio-concretes for structural applications. A series of uniaxial compression tests were conducted on different BCB formulations containing varying bamboo content, followed by a comprehensive analysis of the material's mechanical behaviour.
The results revealed that increasing the proportion of bamboo bio-aggregates led to a significant reduction in both density and compressive strength. The apparent density of the BCBs ranged from 1.71 to 1.91 g/cm³, with the highest densities observed in mixtures containing the least bamboo. As the bamboo content increased from 15% to 30%, the compressive strength of the bio-concrete decreased by up to 43% after 28 days. This reduction in strength is largely attributed to the porous nature of the bamboo aggregates, which reduces the volume of the cement matrix and weakens the bond between the aggregates and the mortar. Moreover, the modulus of elasticity followed a similar trend, decreasing as the bamboo content increased. The BCB-15 mixture, with the lowest bamboo content, exhibited the highest modulus of elasticity, while the BCB-30 mixture, with the highest bamboo content, showed a substantial reduction in stiffness.
Despite the reduction in strength and stiffness, an important finding of this study is the increase in ductility observed in bio-concretes with higher bamboo content. The Poisson's ratio of the bio-concretes ranged from 0.36 to 0.43, significantly higher than the typical range for conventional concretes, which is around 0.1 to 0.2. This indicates that bamboo bio-concretes, particularly those with higher bio-aggregate content, exhibit greater lateral deformation under compressive loads, resulting in a more ductile behaviour. This increased ductility is advantageous in applications where flexibility and energy absorption are important, such as in seismic zones or in structures subject to dynamic loads.

Furthermore, the study evaluated the applicability of various constitutive models in describing the stress-strain behaviour of bamboo bio-concretes. Initially, the standard models from Eurocode 2 and Model Code 2010 were used to predict the compressive behaviour of the material. However, these models failed to

accurately capture the post-peak behaviour observed in the experimental data, particularly for mixtures with higher bamboo content. Both models predicted a more brittle failure than was observed experimentally. To address this discrepancy, the Popovics model was applied, with adjustments made to the elastic modulus factor to better reflect the behaviour of the bio-concretes. This modified model provided a much closer fit to the experimental data, particularly in the post-peak region, where the gradual reduction in stress observed experimentally was better represented.

The findings of this study are highly relevant for the future development and application of bamboo bio-concretes in the construction industry. The results demonstrate that while increasing the content of bamboo bio-aggregates reduces the strength and stiffness of the material, it also enhances its ductility, making it suitable for specific structural applications that require flexibility. Additionally, the study highlights the need for further refinement of constitutive models to accurately predict the mechanical behaviour of bio-concretes incorporating irregularly shaped, larger bio-aggregates.

In conclusion, this research contributes valuable insights into the mechanical performance of bamboo bio-concretes, particularly in relation to the use of waste-derived bamboo bio-aggregates. By leveraging industrial byproducts and focusing on sustainable material usage, the study underscores the potential of bamboo bio-concretes as a viable alternative in eco-friendly construction practices. Future research should continue to explore the optimization of bio-concrete formulations and the development of accurate predictive models to fully realize the potential of these sustainable materials in structural applications.

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Bio-Based Building Materials and Nature-Integrated Construction Technologies

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Keywords: Bio-based Building Materials, Construction Technologies, Low-carbon Strategies.

Bio-based materials refer to substances derived from matter that once existed as living organisms. In the context of sustainability, this term encompasses materials produced from renewable biological sources such as plants (primarily by-products of the agro-industrial and forestry), animals, enzymes, and microorganisms including bacteria, fungi and yeast.

The use of bio-based building materials dates back to early civilizations, reflecting a longstanding and diverse tradition in construction practices. For instance, felt was traditionally used as an external shell in *Yurts* in Central Asia; tar served as a waterproofing membrane in the *Hanging Gardens of Babylon*; and plant-based and animal-derived substances such as egg white, wool, oils, were incorporated into *Khorasan mortars* as performance-enhancing additives to improve strength, elasticity, or water resistance.

Although bio-based building materials have been employed for centuries, their significance has increased in recent decades due to growing environmental challenges associated with conventional construction materials and technologies. Traditional construction materials and methods, known for their carbon-intensive and energy demanded nature, make the construction sector one of the most environmentally impactful industry. Its operations extend beyond the built environment, often resulting in ecosystem degradation, depletion of natural resources, and excessive waste generation. In contrast, bio-based building materials-characterised by properties such as sustainability, biodegradability, abundance, low cost, minimal environmental impact and non-toxicity – are gaining renewed importance as alternatives to conventional building materials.

Therefore, the integration of sustainable materials into modern construction practices has become not only preferable but essential. This shift aims to reduce greenhouse gas emissions, promote resource efficiency, and lower energy use throughout a material's entire lifecycle- from extraction to disposal. Such an approach not only addresses urgent ecological concerns but also aligns with global efforts to achieve carbon neutrality and enhance resilience to climate change.

In this context, the study aims to investigate bio-based materials and their integration with emerging technologies to highlight their environmental benefits within the framework of sustainability goals. It seeks to demonstrate that bio-based building materials hold significant potential compared to conventional materials in the terms of ecological impact.

The study used a qualitative research methodology based on literature review and structured into two main phases. First, bio-based building materials were classified within the built environment through a comprehensive review of literature. Following this classification, a second literature review was conducted to identify case studies on the application of bio-based materials and to examine the emerging technologies that enable their integration into contemporary architectural and construction practices. As a result of this two-stage review process, bio-based materials were categorized into three main categories based on their functions: (1) Structural and infrastructural components, (2) Façade and surface materials and components, and (3) Performance -enhancing materials and components. Four different case studies were discussed under each category and comparative charts were created to analyse the findings. This classification and comparative charts not only provide a clear understanding of the functional diversity of bio-based materials but also offer a framework for analysing their contemporary applications and technological developments in construction sector.

The findings of the study demonstrate that bio-based materials offer advantages such as biodegradability, renewability, reduced environmental impact, and compatibility with contemporary architectural and construction practices. Ultimately, the study emphasizes the importance of incorporating bio-based

building material alternatives into construction sector to mitigate climate change effects and support the transition toward low-carbon footprint.

Bio-based materials to reduce non-renewable resources use in construction: a products' analysis

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Keywords: circular processes; wood fibre; hemp; cork; rice waste..

Frans Timmermans declared, at the presentation of the new Circular Economy Action Plan (CEAP) in 2020, that only 12% of materials and secondary resources are reinserted into the economic process. For this reason, the CEAP aims to ensure a more circular process.

At European level, the construction sector consumes high quantities of raw materials, as reported by Eurostat Domestic Extraction indicator which shows the quantity of raw materials withdrawn and used in the economic process. Indeed, the internal consumption of materials calculated by Eurostat in 2023 is equal to 55% for non-metallic minerals, other products, and waste for final treatment and disposal; 23% for biomass; 17% for fossil fuels; and 5% for metallic ores. In Italy, the consumption of resources is quantified by the Italian National Institute of Statistics, which in 2018 estimated the extracted quantity of raw materials such as biomass, minerals and fossil fuels at 317 million tonnes; of these, 67% concern metallic and non-metallic minerals, 94% of which include elements used in the construction sector such as sand, gravel, limestone and clay. Therefore, non-metallic minerals are the most extracted and used. Some consider them renewable resources, but since their regeneration requires a period of time not comparable with a single man's existence, it is more correct to frame them as non-renewable; in fact, these can be extracted in limited quantities and will be exhausted due to overexploitation. In this scenario, to limit the depletion of resources, it is necessary to find a valid alternative to the use of non-renewable materials such as the use of bio-based products.
Over the years, various definitions of bio-based have been developed, which agree on the fact that these are identifiable as materials derived in part or in total from biological organisms. Starting from this assumption, an analysis was carried out on four bio-based materials to verify which building products are present on the Italian market and whether the building sector is actually changing. The materials selected are wood fibre, hemp, cork and rice waste: the first two are more present on the market compared to the other two, one due to the cost and the other because only recently experimentation with food waste has begun. These four materials are all by-products or derive from other primary processes, so their use in the construction sector is not the primary sector of use. Once the four bio-based materials had been selected, the research method focused on identifying producers through an analysis of three online portals specialised in the sale of construction products in Italy and on the ECO Platform and EPD Italy sites. In total, 253 products were analysed which constitute a database capable of describing the main characteristics of the products on the market: reference data, composition, laying and installation methods, applications, function, technical data and certifications.

Starting from this data, infographics were created to allow, for each bio-based material taken into consideration, to highlight: the type and quantity of products in the Italian market; their composition and the origin of any added material; and, for multi-material products, which other components are added. The collected data highlighted that the four bio-based materials examined are usually combined with other components of mineral, synthetic or natural origin: for the first, the most recurring elements are hydraulic

and aerial lime and Portland cement; concerning the second resins and polyester fibres are used; while for the third mostly elements of vegetal origin as natural additives, jute and cellulose are used. In particular, by analysing the database products, 58% of those made of cork are composed of natural material alone, while 39% of wood fibre, 50% of hemp and 77% of rice waste are combined with mineral elements. Future research developments will include an integration of the database with other bio-based materials employed in construction and present on the Italian market, to better define the trend in the use of natural resources. Furthermore, other investigations will be carried out to delve deeper into some aspects such as: processing phases; recycling or recovery methods; type and sustainability of packaging; possible difficulties regarding the diffusion of natural-based products on the market. To collect this data, a semi-structured interview is being constructed to be submitted to the manufacturing companies whose products are present in the established database. This research is necessary to understand whether marketed natural materials are actually sustainable, as declared by producers, and to what extent they can actually be recycled or reused in the production cycle.

In conclusion, it is necessary to change the way in which we produce and use products by creating a more circular process that allows us to conserve what is taken and transformed once it has reached its end-of-life.

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Bond Performance of Bamboo in Bio-Based Cementitious Composites Using Castor Oil-Based Resin

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Keywords: Bamboo; Bamboo reinforcement; Bond strength; Analytical modelling

The increasing demand for sustainable solutions in the construction sector has driven the search for alternative materials that reduce environmental impact and enhance energy efficiency. Bamboo has emerged as a promising material due to its rapid growth, high tensile strength, and widespread availability, particularly in Brazil. Its application as structural reinforcement in concrete can significantly reduce carbon emissions; however, technical challenges still limit its use, such as low adhesion to the cementitious matrix and long-term durability concerns. Therefore, advancements in bamboo surface treatments are essential to optimize its structural performance and expand its viability in construction applications.

This study investigates the application of castor oil-based waterproof resin as a surface treatment to improve the adhesion of bamboo to the cementitious matrix, evaluating its effectiveness compared to untreated bamboo and bamboo treated with a combination of resin and sand. Pull-out tests were performed on bamboo strips measuring 6 × 6 mm under three conditions: untreated, treated with castor oil-based resin, and treated with castor oil-based resin combined with sand. Additionally, an analytical model was developed to simulate the interaction between bamboo and the cementitious matrix during the pull-out process. This model assumes that the bamboo strip behaves in a linearly elastic manner, the cementitious matrix is perfectly rigid, and the interaction between both follows a bond-slip law (τ-s) that remains invariant along the fiber length.

The methodology involved the characterization of bamboo and industrial residues used in the formulation of the cementitious composite, followed by the production of a bio-based cementitious composite composed of 35% bamboo particles derived from industrial waste, incorporated into a cementitious matrix containing 40% cement, 30% metakaolin, and 30% fly ash. The bamboo strips underwent surface treatment with castor oil-based resin or castor oil-based resin combined with sand before being molded into cubic specimens (50 × 50 × 50 mm^3), ensuring an embedment length of 50 mm. Pull-out tests were then conducted to assess the bond strength under different treatment conditions. Concurrently, the bio-based cementitious composite was physically and mechanically characterized, yielding mean values of density of 1267 kg/m^3, compressive strength of 10 MPa, and an elastic modulus of 4 GPa.

The Mosso bamboo species (*Phyllostachys pubescens*) used as reinforcement exhibited a tensile strength of 158 MPa and an elastic modulus of 7 GPa. The pull-out test results indicated that untreated bamboo exhibited a bond strength of 0.45 MPa, while treatment with castor oil-based resin increased this value to 0.74 MPa, representing a 64.4% improvement. The combination of castor oil-based resin with sand further enhanced adhesion, reaching 1.11 MPa, an increase of 147% compared to untreated bamboo and 50% compared to bamboo treated only with resin. The improvement in adhesion with castor oil-based resin treatment can be attributed to its ability to fill micro-irregularities on the bamboo surface, enhancing chemical and mechanical

compatibility with the cementitious matrix. The addition of sand further increased adhesion, as the sand particles acted as mechanical anchorage points, increasing surface roughness and reinforcing the bamboo-matrix interface.

The results of this study confirm that bamboo can be a viable alternative as reinforcement in cementitious composites, provided its adhesion is improved. The castor oil-based waterproof resin proved to be a sustainable and efficient alternative to epoxy resin, significantly enhancing bond strength. Furthermore, the combination of resin and sand proved to be the most effective treatment, increasing the anchorage interface and improving stress transfer between the fiber and the cementitious matrix. These findings reinforce the potential of bamboo as structural reinforcement, facilitating its use in sustainable applications and promoting the reuse of industrial waste in the construction sector.

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Characterisation and Technical Feasibility of Remanufactured Mycelium Biocomposites for Insulation Purposes

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Keywords: Mycelium biocomposites, Biobased construction, Insulation, Remanufacturing.

As sustainable building methods are gaining prominence, the implementation of viable alternatives is becoming an important focus for research. Mycelium biocomposites serve as potential biobased alternatives to conventional insulation materials within the construction industry, such as polystyrene and rockwool. As the material is approaching the market, exploration of the various end-of-life possibilities is necessary. Biodegradability is a possible solution, and the most referred to for biobased materials; however, if it is possible to extend the lifespan without comprising the properties, it gives mycelium biocomposites a competitive advantage upon entering the market. This study investigated the ability to remanufacture mycelium biocomposites using varying ratios of used and new substrate, to determine which is optimal without compromising the material properties. In addition to evaluating the optimal substrate ratios for remanufacturing, mycelium biocomposites comprised of *Ganoderma lucidum* and of *Pleurotus ostreatus* were also investigated. Each mycelial strain interacts with the substrate in a unique manner and have different growth mechanisms; therefore, the efficacy to remanufacture used substrate with different strains is an important point to address. These biocomposites are intended for insulation; therefore, moisture behaviour, mechanical properties, thermal conductivity, and macro-/microstructural investigation will elucidate the characteristics of the remanufactured mycelium biocomposites.

The remanufacturing process is shown by the schematic in Figure 1. The procedure of this study utilized liquid spawn of malt extract agar to inoculate the autoclaved substrate, which was then moulded and placed in a climate chamber for approximately 11 days. During this time, the mycelium will grow and bind the substrate together. After sufficient incubation and growth, the mycelium biocomposite was placed in an oven at 65°C for 24 hours to deactivate the mycelium. To remanufacture, the initial sample was shredded and autoclaved, and then the same procedure to inoculate, incubate, and dry the samples followed. An additional step of adding nutrients was incorporated when preparing the samples to promote mycelial growth. The key difference between the procedures was the amount of new substrate incorporated to remanufacture the sample. The substrate used throughout the study was rapeseed straw, and Table 1 details the ratios of used substrate to new substrate investigated in this study. The remanufacturing process was identical for samples comprised of *G. lucidum* and *P. ostreatus* to ensure a valid comparative analysis.

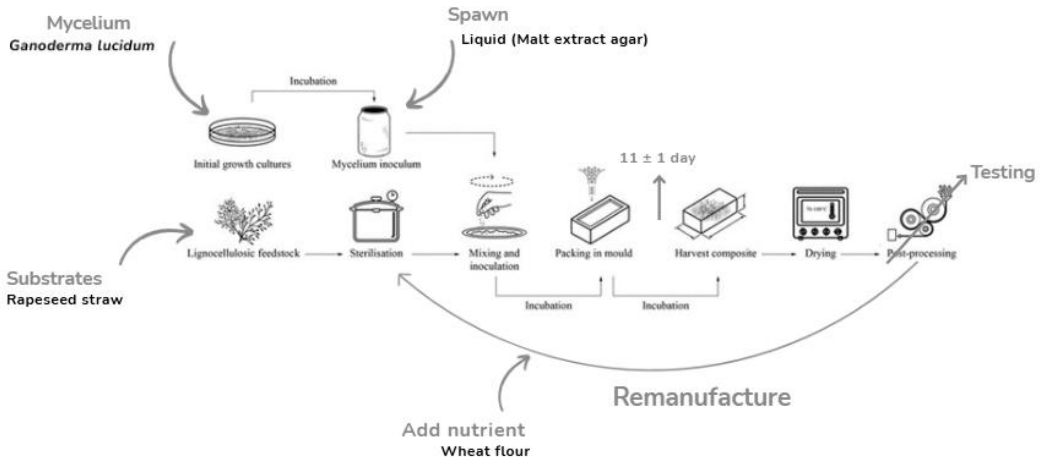

Figure 1. Schematic of the remanufacturing process for mycelium biocomposites

Table 1. Investigated substrate ratios for remanufacturing

Sample ID (Species-Used %)	Used Substrate (%)	New Substrate (%)
GL/PO – 0	0	100
GL/PO – 25	25	75
GL/PO – 50	50	50
GL/PO – 75	75	25
GL/PO – 100	100	0

The experimental results from this study show that full remanufacturing, which was cycling 100% of the used substrate, was possible for mycelium biocomposites comprised of *G. lucidum* and *P. ostreatus*. However, samples comprised of *G. lucidum* had better results for remanufacturing with rapeseed straw as the substrate. This was determined by how well the samples grew after the remanufacturing process based on the whiteness coverage of the sample, and was linked to the effect this had on the investigated properties. From the remanufacturing process, degradation of used substrate quality was noticed based on visual inspection as well as the influence on numerous factors including the nutrients available for the mycelium, water within the substrate, and density. Variation of density had an impact on the compressive strength and thermal conductivity results, as well as the binding between the mycelium and substrate. However, values for compressive strength and thermal conductivity were still within the range of that required for an insulation material. For moisture behaviour, samples with higher amounts of used substrate were more hydrophilic as compared to samples with more new substrate.

This initial study showed that remanufacturing is a possibility to extend the lifespan of mycelium biocomposites for insulation purposes. Additionally, remanufactured mycelium biocomposites could even be used for other applications, such as packaging after its use as an insulation construction material. Varying the amount of used and new substrate resulted in different properties based on the state of the substrate. Further research should be conducted into the exploration of more mycelial strains, different substrates, various nutrient sources, and post-processing methods, such as possible biobased coatings, to fully understand the potential of the end of life possibilities for mycelium biocomposites.

Comparative flexural performance of different hemp-reinforced composites

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Keywords: metakaolin, hemp fibre, acid-activated geopolymer, fibre deterioration

Introduction

Plant fibres are abundant renewable resources that have great potential as sustainable alternatives to fossil fuel-derived polymer products for producing construction materials. Processed plant fibres, such as hemp fibre, can improve mechanical performance and reduce embodied carbon in cementitious composite construction products. Reinforcing geopolymer binders with hemp fibres is not yet fully understood and, in particular, the effects of different chemical activators on the mechanical performance has not been investigated.

Methodology

3-point bending samples (40 × 15 × 8 mm) were prepared using the mix designs shown in Table 2.

Materials

Geopolymer: MetaMax® metakaolin from BASF was used as the precursor in both alkaline-activated and acid-activated geopolymer binders. Commercial sodium silicate solution (VWR), commercial-grade sodium hydroxide pellets with 98% purity, and distilled water were used for the alkaline activator. Commercial phosphoric acid with 85% purity and distilled water were used for the acid activator.

Cement: CEM I from Dragon Alfa was used as a Portland cement based control.

Hemp fibre: from East Yorkshire Hemp. After removing the shiv, the hemp fibres were cut to approximately 12mm. Then, the hemp fibre was oven-dried at 105 °C until there was negligible mass change. Hemp fibre-reinforced samples contained 5% fibre content by mass.

Curing

Alkali-activated geopolymer samples were cured at 60 °C for 24 hours. Acid-activated geopolymer samples were sealed in plastic bags and stored at ambient temperature for 24 hours, then moved into an oven set at 60 °C for another 24 hours before demoulding. Cement matrix samples were sealed and cured at ambient temperature. All the samples were sealed and stored at ambient temperature until testing.

Table 2 Mix design in all samples

Alkali-activated geopolymer				
Name	Si/Al	Na/Al	H/Al	Fibre content (%) by mass
alk15	1.5	1.0	13	0
alkf15	1.5	1.0	13	5
Acid-activated geopolymer				
Name	(Si+P)/Al	P/Al	H/Al	Fibre content (%) by mass
ac200	2.0	1.05	12	0
acf200	2.0	1.05	12	5
Cement paste				
Name	Water/cement ratio (w/c)			Fibre content (%) by mass
ce	0.5			0
cef	0.5			5

Results & Discussion

Optical microscope

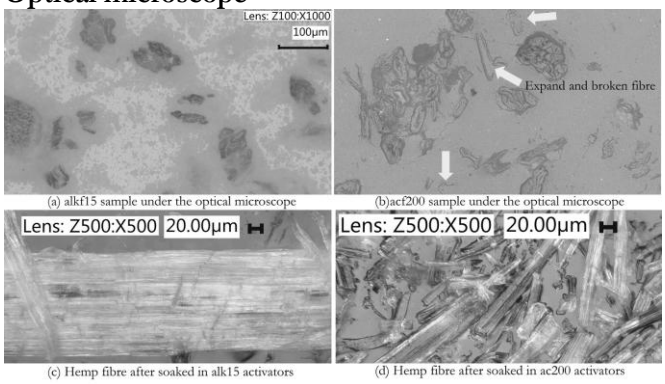


Figure 2 (a) and (b) show the hemp-reinforced alkali-activated (alkf15) and acid-activated (acf200) geopolymer composites. In

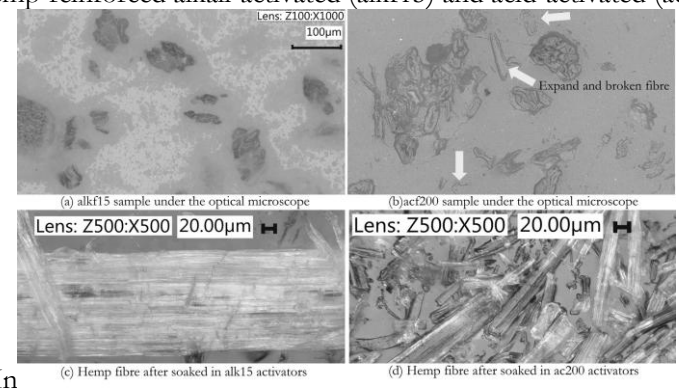
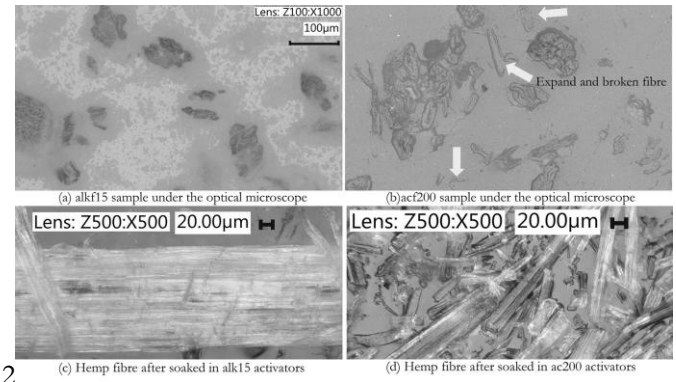


Figure 2



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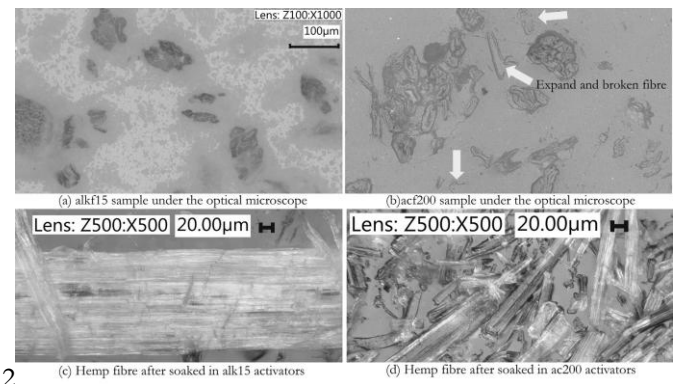


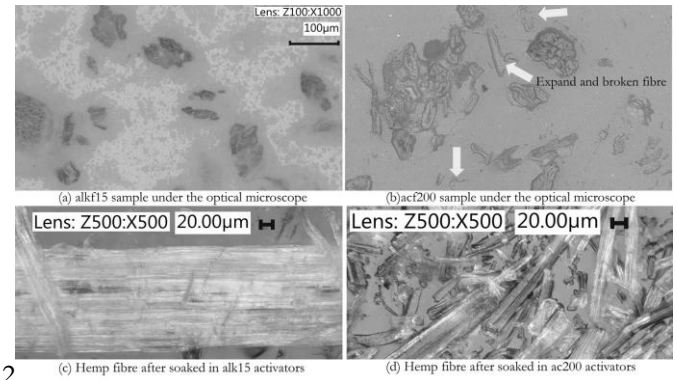


Figure 2

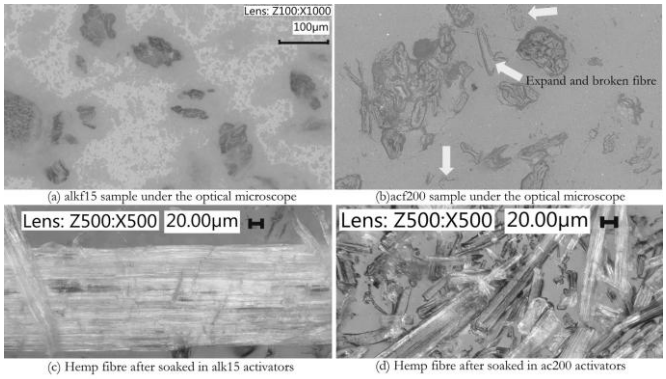


Figure 2

Figure 2(b) the individual filaments were swollen, expanded and broken down in the acid activator, compared to the alkali activator. The extend of deterioration is more clearly seen when the hemp fibre was directly soaked and reacted with activators.

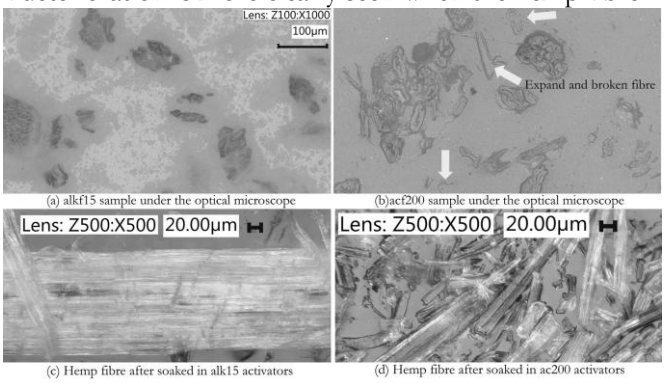


Figure 2 (c) and (d)show the hemp fibres soaked in the acid activator have broken down into smaller pieces and changed colour, compared to those in the alkali activator indicating deterioration.

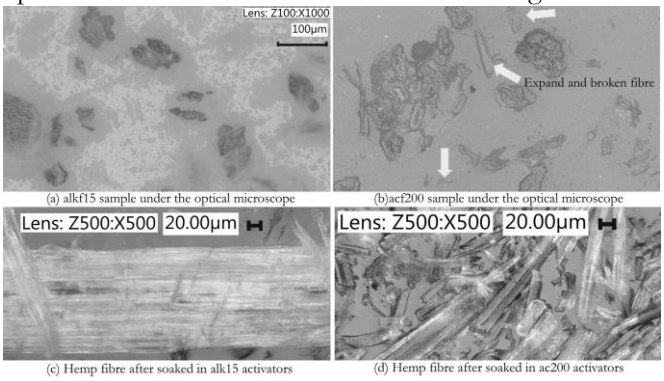


Figure 2 Optical microscope images for composite and hemp fibres soaked in activators

Flexural performance

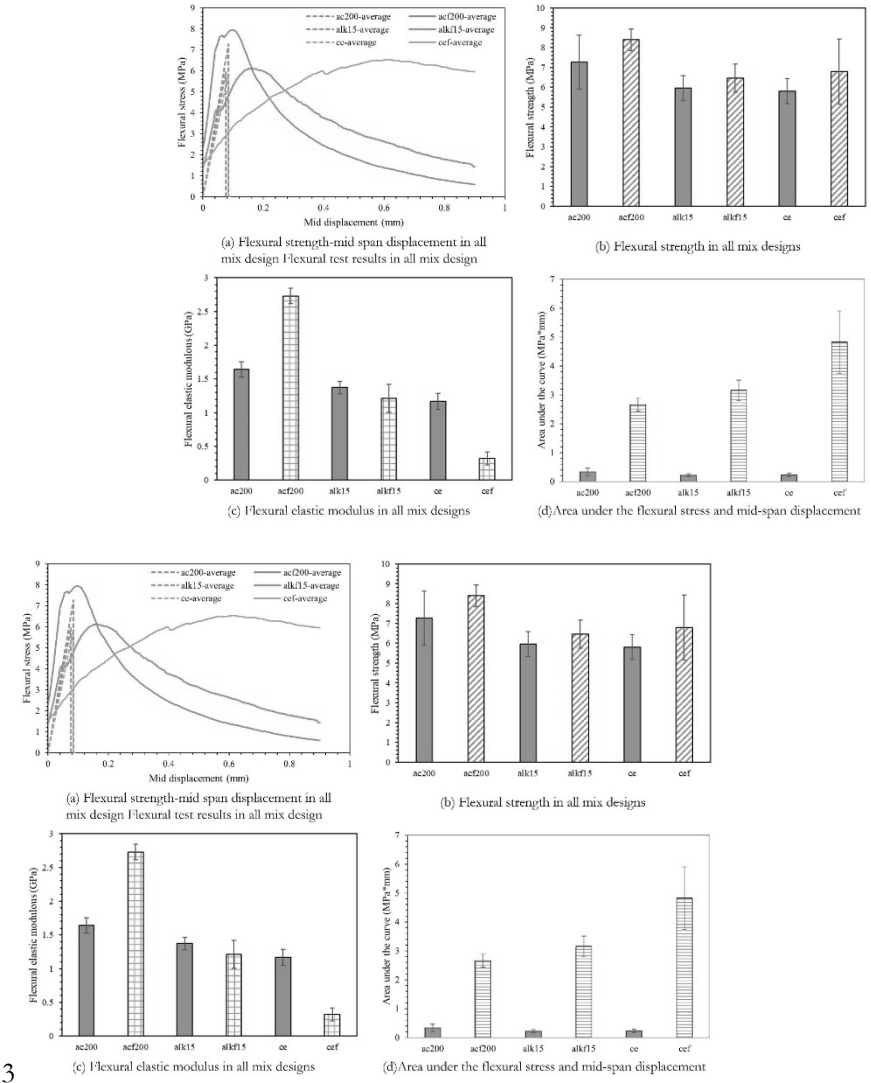
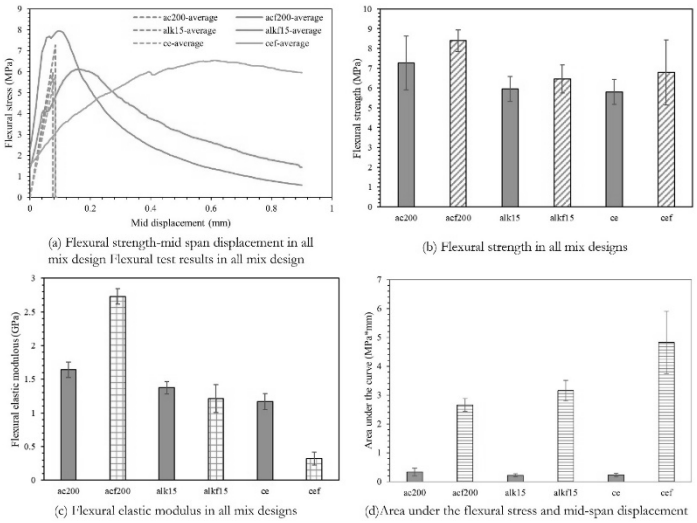


Figure 3

Figure 3 (a) and Figure 3 (b) indicate that adding hemp fibres improves the flexural strength in all mix designs. The hemp fibres successfully controlled the opening of small cracks and dispersed the force over a larger area. However, the flexural elastic modulus behaves differently, as shown in Figure 3 (c). An increase in flexural elastic modulus is observed in acid-activated geopolymer when hemp fibres are added,

but for the alkali-activated and cement matrices, there was a decrease in flexural elastic modulus.



(a) Flexural strength-mid span displacement in all mix design Flexural test results in all mix design

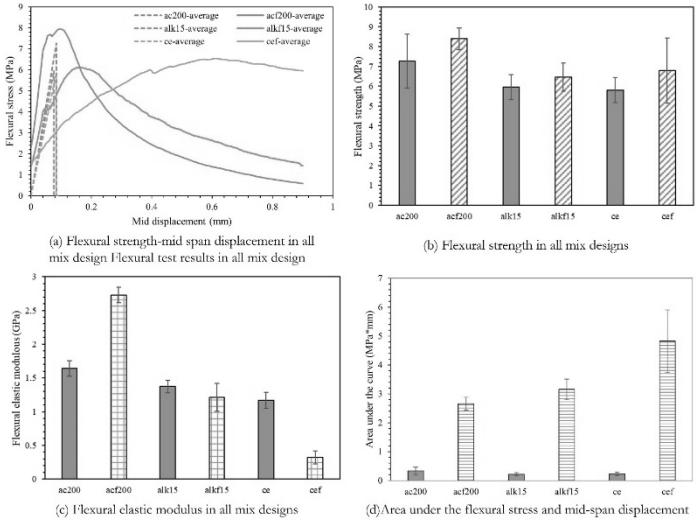
(b) Flexural strength in all mix designs

(c) Flexural elastic modulus in all mix designs

(d)Area under the flexural stress and mid-span displacement

Moreover, Figure 3

Figure 3(d) shows that adding fibres greatly increases the area under the flexural stress and mid-span displacement graph (up to a maximum displacement of 0.9 mm), representing the ability to absorb energy and increased ductility. In acf200, the same hemp fibre content does not absorb as much energy as in the alkf15 and cef matrices, and has a lower post-peak residual strength, indicating that the effects of fibre deterioration under acid conditions indicated in Figure 1 has a negative effect on ductility even though it does not have a negative effect on peak strength or elastic modulus (which is governed more by the matrix).



(a) Flexural strength-mid span displacement in all mix design Flexural test results in all mix design

(b) Flexural strength in all mix designs

(c) Flexural elastic modulus in all mix designs

(d)Area under the flexural stress and mid-span displacement

Figure 3 Flexural results for different mix designs

■ Conclusion

Adding hemp fibre increases flexural strength, energy dissipation, and mid-span displacement in different matrices, as well as transitioning from a brittle failure for geopolymers without fibres, to a more ductile failure with fibres. Hemp fibres were found to deteriorate under acid conditions, such as in the acid-activated geopolymer matrix, causing the flexural elastic modulus in the composite to be higher than in the plain acid geopolymer specimens, but with reduced ductility compared to the alkali-activated geopolymer and Portland cement based matrices. The variations in mechanical properties are most likely linked to the different chemical reactions that take place at the interfaces of the binder matrix and the reinforcing fibres, which will be investigated in future studies.

Decoding Societal Attitudes to Bamboo in Construction

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Keywords: Full-culm bamboo, sustainability, societal attitudes, colonialism, eurocentrism.

Bamboo is an exceptional construction material with a latent potential to meet the increasing demand for buildings while addressing global carbon emissions. With a strength comparable to high-grade hardwoods, bamboo is accessible and versatile, making it highly suitable for construction in tropical low- and middle-income countries (LMICs), the part of the world where the demand for new construction will continue to increase well into the 21st Century. However, despite advancements such as recent international standards (ISO 22156, 22157, and 19624), societal attitudes and misconceptions continue to limit its wider acceptance in the construction industry.

This paper investigates the sociological non-technical barriers affecting the use of full-culm bamboo, the round pole, most sustainable form when used locally. Historical biases stemming from colonial-era architectural theory are traced to today's architectural education and praxis. A view of natural materials as inferior to geometric purity and artificial materials are have resulted in a lack of design awareness and restricted industry knowledge. This vacuum has than allowed unsubstantiated myths result in inappropriate usage and a lack of contemporary critique within the architectural community.

Through a literature review the paper identifies key challenges such as the durability of bamboo structures. Findings reveal that durability concerns, compounded by issues of material quality, are the most significant hurdles. These are addressed through a framework comprising seven critical factors for design professionals to integrate into the construction process.

The paper underscores the need for nuanced understanding and communication of bamboo's capabilities among design professionals to counter negative perceptions and myths. By championing its sustainable and versatile properties, professionals can exemplify and develop bamboo as a mainstream construction material. Good design for bamboo, can drive broader acceptance of bamboo in contemporary construction practices.

Development of Bio-based Engineering Wood Products Using Recycled Wood and Biochar

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Keywords: waste wood utilisation, biochar, engineered wood products, sustainable building materials, particleboard

The growing need for sustainable, eco-friendly materials in construction has driven the exploration of biobased composites such as engineered wood products. The potential of using logs and lumber more efficiently by incorporating lower-grade wood of various sizes has catered to different applications and is a more sustainable alternative to traditional timber panels. These panels have gained popularity for their versatility, strength and dimensional stability, making them ideal for structural applications such as beams, floors and prefabricated wall panels. However, the global timber shortage and the increasing volume of wood waste in landfills present a significant challenge to the continued reliance on virgin timber resource for these panel production, highlighting the need for alternative raw materials such as recycled wood, to ensure both resource efficiency and environmental sustainability.

This study focuses on the development of engineering wood products utilizing recycled wood and biochar, addressing the dual challenges of waste wood utilization and carbon sequestration. While traditional engineered wood materials often rely on virgin timber and synthetic adhesives, this research takes a novel approach by integrating biochar, a carbon-rich byproduct of biomass, to enhance the mechanical and physical properties of these panels. Additionally, a bio-based adhesive is employed to eliminate the risk of formaldehyde emissions commonly associated with conventional engineered wood products.

In this research, recycled wood flakes are incorporated with varying proportions of biochar in a resin-based matrix to fabricate particleboard, a popular type of engineered wood panels. Bio chair obtained from a production plant operated by Radial Timber Australia Ltd is mixed in proportions varying form 0-30% with recycled wood flakes. These are then oven dried at 80°C for 24 hours to remove any moisture content. The bio epoxy resin and fast hardener (AMPRO™ Bio) provided by Gurit Services AG, Zuric are mixed to a 3:1 ratio for 2 minutes. Once the epoxy is mixed, it is sprayed onto the wood mixture while mixing continuously for 5 minutes in amounts of 16% on the dry weight of the wood and biochar particles. Paraffin wax and water are added in amounts of 3% and 5% respectively based on dry weight of the wood particles, and 1% of ammonium sulphate hardener added based on the resin content. This mixture is then laid out onto an aluminium mold lined with non-stick paper, and pressed on a hydraulic press at room temperature under a rate of 0.1 mm/s. Once the pressing is complete, the panel is clamped in place for 6 hours until the bio-resin is cured. The produced panels are then removed from the mold and conditioned at 20°C and 65% relative humidity for 7 days. The panels are then cut into samples according to the guidelines given in AS/NZS 1859 and testing for modulus of rupture (MOR), modulus of elasticity (MOE), water absorption

and thickness swelling are conducted. A microstructural analysis through scanning electron microscopy (SEM) is also conducted to investigate the bonding mechanism and biochar distribution within the matrix.

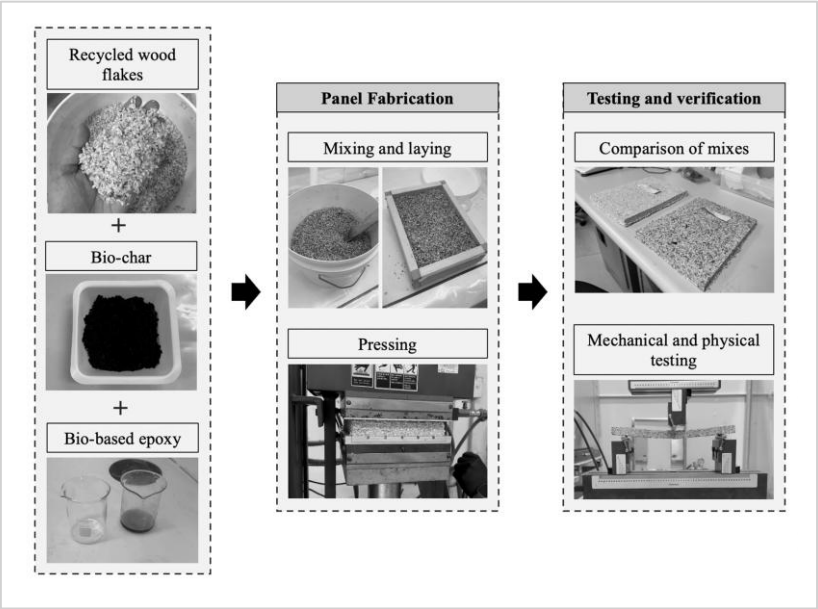

Figure 4: Materials used, fabrication method and testing of bio-based engineered wood panels

The results reveal that the inclusion of biochar significantly improve the mechanical and physical properties of the composites. Panels with a biochar content of 10–30% exhibit an increase in in modulus of rupture (MOR) and modulus of elasticity (MOE) compared to those without biochar, demonstrating their suitability for loadbearing applications. Specifically, samples with 30% biochar content show an MOR increase of approximately 11% and an MOE enhancement of 14% relative to control panels. This improvement is attributed to biochar's ability to reinforce the wood matrix and enhance internal bonding.

Furthermore, the biochar-modified composites show enhanced water resistance and dimensional stability, making them competitive with traditional engineered wood products. The hydrophobic nature of biochar likely contributes to these improvements by limiting moisture penetration and minimizing swelling under humid conditions. Microstructural analysis through scanning electron microscopy (SEM) further confirms the uniform dispersion of biochar particles within the matrix, reinforcing the wood-binder interface and improving stress distribution. The enhanced interfacial bonding is particularly evident in samples with optimized biochar content, where fewer voids and improved matrix densification are observed.

Overall, the incorporation of biochar in recycled wood composites not only improves mechanical strength and moisture resistance but also enhances the sustainability of engineered wood products. Future studies will assess the long-term durability of these composites and explore potential refinements in resin formulation to further optimize mechanical performance.

In conclusion, the successful integration of biochar into recycled wood composites presents a sustainable and high-performance alternative to conventional engineered wood products, demonstrating significant improvements in mechanical strength, moisture resistance, and environmental impact, paving the way for greener construction materials and advancing circular economy principles in the built environment.

Eco-Efficient Buildings: Real-Time Monitoring of Thermal Conductivity in Bio-Based Materials

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Keywords: monitoring, thermal conductivity, bio-based materials

The imperative to transition towards sustainable and healthy building practices has placed bio-based materials at the forefront of architectural innovation. Despite their promise, a significant knowledge gap persists concerning their dynamic thermal performance in real-world environments. While laboratory tests establish provides valuable baselines, the actual effectiveness of bio-based insulation is significantly affected by environmental variables, including moisture levels, temperature variations, and material aging. This state-of-the-art review emphasizes the critical importance of real-time sensor monitoring for thermal conductivity in bio-based materials. This monitoring is not simply an academic exercise; it is an indispensable tool for guaranteeing the long-term energy efficiency and structural soundness of buildings utilizing these materials. Furthermore, it directly impacts the well-being of building occupants by ensuring a stable and healthy indoor environment. By bridging the gap between laboratory data and real-world performance, we can fully realize the potential of bio-based building solutions.

Currently, thermal transmittance (U-value) is primarily determined using the Guarded Hot Plate (GHP) method. The GHP method, standardized in ISO 8302 and ASTM C177, which is a primary technique for determining the thermal transmittance (U-value) of materials under controlled laboratory conditions. This method establishes a steady-state heat flow through a test specimen positioned between a hot and cold plate. The "guarded" design minimizes lateral heat loss, ensuring one-dimensional heat transfer. By accurately measuring the temperature difference across the specimen and the corresponding heat flux, the U-value is calculated. This method provides highly precise data, crucial for evaluating the thermal performance of insulation materials and building components.

This article describes the development of an innovative sensor monitoring application designed for real-time measurement of thermal transmittance (U-value) in bio-based constructions. In collaboration with electronics students from Avans University of Applied Sciences a test setup is realized. This new Measurement configuration integrates heat flux meters, which quantify heat flow through the building component, alongside temperature sensors which precisely record both surface and ambient air temperatures, providing a comprehensive dataset. The system's design emphasizes accurate, continuous data collection, crucial for understanding the dynamic thermal performance of bio-based materials.

The sensor setup will be applied to existing straw-insulated construction, in which volumetric moisture content with Time Domain Reflectometry (TDR) sensors an temperatures sensors inside the constructions is already measured and completed with a weather station providing environmental data.

It is installed on The Green Village location in Delft (The Netherlands) which is an open-air living laboratory dedicated to the exploration and implementation of sustainable innovations and technologies

within the built environment. Located on the campus of Delft University of Technology, this unique facility provides a real-world testing ground for cutting-edge solutions aimed at addressing the pressing challenges of environmental sustainability.

The research is focused on the development of a practical and accurate method to monitor the dynamic thermal performance of bio-based insulation materials under real conditions. By integrating heat flux, temperature, and moisture measurements, we seek to accurately assess performance under varying environmental conditions. This comprehensive approach offers a unique opportunity to analyze how factors like humidity and temperature fluctuations impact the U-value. Ultimately, the research will provide valuable insights for optimizing the sustainability and energy efficiency of bio-based constructions, contributing to the advancement of eco-friendly building practices. This data-driven analysis will enhance our understanding of these materials' real-world performance. The new developed comprehensive dataset can later be used by data scientists to demonstrate correlations and causal relationships using advanced machine learning models.

Effect of self-assembled cellulose nanofiber (SCNF) on interface bonding and mechanical properties of engineered geopolymer composites (EGC) based on in-situ polymerization

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Keywords: engineered geopolymer composites, cellulose nanofiber, interface, fiber pullout, mechanical properties.

As a promising substitute to ordinary Portland cement (OPC), geopolymer exbibits excellent mechanical properties, thermal properties, durability and environmental advantages. However, their inherent brittleness and shrinkage limitations hinder broader applications. To address these limitations, extensive research has been conducted on engineered geopolymer composites (EGC), aiming to enhance their toughness by integrating fibers into the matrix. Cellulose nanomaterials (CNM), derived from plant fibers, contain abundant hydroxyl groups, imparting hydrophilicity, hygroscopicity, and high surface activity. With an average width of approximately 100 nm and a length of 2000 nm, CNMs possess nano-scale reinforcement effects that have been shown to enhance the mechanical properties of geopolymer. However, their tendency to aggregate poses a significant challenge. For the multi-scale and multi-phase composite materials, it is essential to modify geopolymer-based material at different scales to optimize structural and mechanical performance. This study explores the potential of multi-scale synergistic reinforcement using CNM and polyvinyl alcohol (PVA) fibers to enhance the mechanical properties and shrinkage resistance of metakaolin-based geopolymers (MKG), contributing to the advancement of sustainable construction materials.

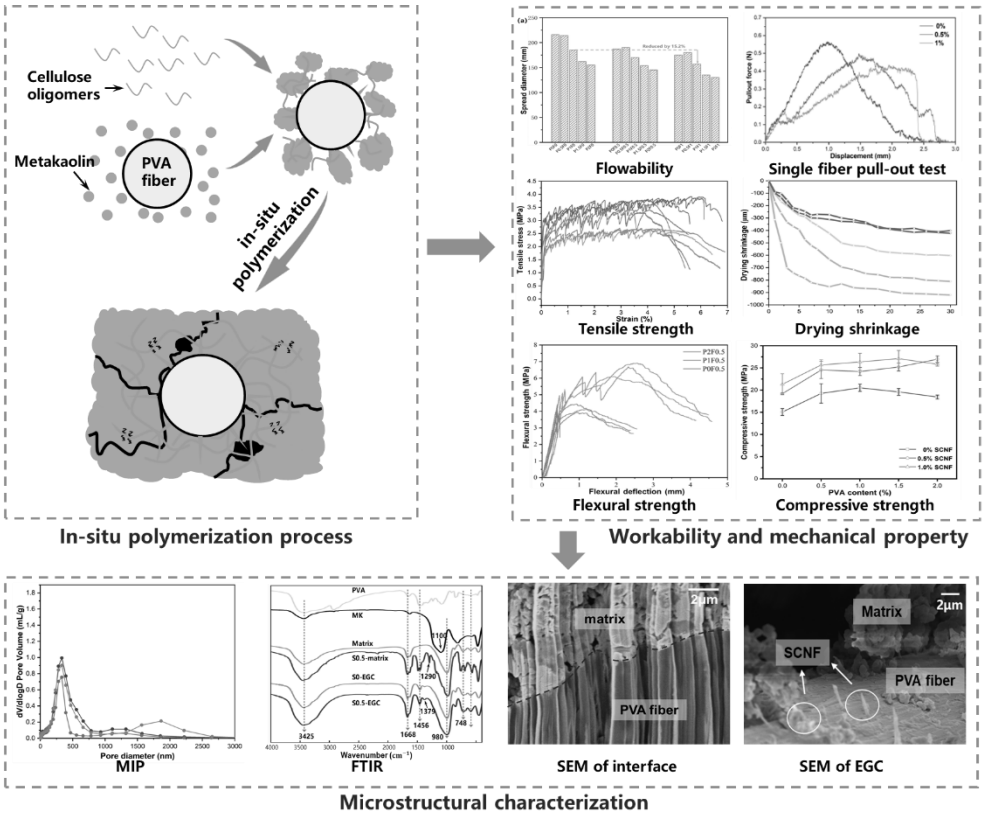
To ensure the uniform dispersion of CNMs in the geopolymer matrix, cellulose fibers were first decomposed into oligomers via freeze-thaw treatment, followed by in-situ polymerization to induce self-assembled cellulose nanofibers (SCNF) within the MKG pastes. A comprehensive investigation was conducted on the effects of SCNF at different concentrations (0.5 wt% and 1 wt%) and PVA fiber at varying dosages (1 % and 2 %). This study evaluated the flowability, drying shrinkage, compressive strength, and tensile strength of the MKG. Additionally, scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), and Fourier-transform infrared spectroscopy (FTIR) were employed to analyze the microstructural modifications induced by SCNF. Furthermore, single-fiber pull-out test were performed to assess the interface bonding between PVA fibers and the MKG matrix. The objective was to highlight the synergistic effects of SCNF and PVA fibers in enhancing the performance of MKG.

First of all, according to the results of SEM and FTIR, the size of SCNF increased from 200-300 nm at 12 hours to 2-3 μm at 3 days in the PVA fiber surfaces, MKG matrix, and EGC. Meanwhile, the increased intensities of -CH_2 and C-O bonds, along with Si-O-T (T = Si and Al) bonds, confirmed that the self-assembly of SCNF occurred simultaneously with the geopolymerization process. Second, SCNF could improve mass loss and drying shrinkage of EGC. When PVA fibers dosage was 1 %, the drying shrinkage

was reduced by 40%, and the mass loss was reduced by 39%. When PVA fibers dosage was 2%, the drying shrinkage was reduced by 18%, and the mass loss was reduced by 32%. Third, the addition of SCNF improved the mechanical properties of EGC at both PVA fibers contents. When the PVA fiber dosage was 1%, the pure PVA-reinforced MKG material exhibited a main crack. However, after the incorporation of SCNF, the cracking mold changed, and multiple microcracks appeared. The addition of SCNF enhanced the compressive strength by 29%, the flexural strength by 82%, and the tensile strength by 54.8%. When the PVA fiber dosage was increased to 2%, the compressive strength improved by 45%, the flexural strength by 67%, and the tensile strength by 45%. Finally, Single fiber pull-out test demonstrated that SCNF enhanced the PVA fiber-MKG matrix interface bonding strength. As the SCNF content increased, the initial bond strength increased by 47.7%, while, leading to a decreased in slip-hardening coefficient β from 3.125 to 0.850. SCNF and PVA fibers exhibited a synergistic effect during the cracking process. In the elastic stage, SCNF limited the accumulation of microcracks. As microcracks transitioned to macrocracks, SCNF improved the PVA fiber/matrix interface bonding, increasing the energy required for fiber pull-out and enhancing the overall load-bearing capacity of EGC.

Overall, this research investigates the effect of SCNF on PVA-matrix interface and mechanical properties of EGC. The results show that SCNF as a nano-reinforced material changed the matrix and interface properties. SCNF could improve the strain hardening properties, leading to a reduction of the critical PVA fiber dosage. Under the synergistic effect of SCNF and PVA, a high ductility fiber reinforced geopolymer composite with low drying shrinkage was obtained. This study gives a promising approach for designing interface bonding properties using cellulose nanomaterials and provides valuable insights for developing high-performance geopolymer composites.

Graphic figure



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Effects of Curing Conditions on Stabilized Earthen Building Materials

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Keywords: Earthen material, natural hydraulic lime, air lime, hydrated lime, cement, stabilization

Earthen materials have been a fundamental building resource since ancient times, offering a sustainable and efficient construction method. Anatolia stands out as one of the regions where early earth-based structures have been preserved. Among these, Çatalhöyük is a rare Neolithic example featuring adobe houses with wooden beams. Similarly, the city of Hattusha showcases an urban texture shaped by mud brick construction. Other significant archaeological sites, such as Aşıklıhöyük, İznik Ilıpınar, Acemköyük, Aslantepe, Çayönü, Alacahöyük, and Alişar, also provide insight into the long-standing tradition of earth-based construction in Türkiye. Iznik, a multi-layered cultural center currently on UNESCO's World Heritage tentative list, has been home to numerous civilizations since antiquity in Bursa, Türkiye. The town has managed to preserve a significant number of settlements reflecting regional cultural characteristics in a holistic architectural texture. Many of these settlements, including Elbeyli, Ömerli, and İnikli districts, were constructed using traditional adobe techniques combined with wooden frames. In the Ömerli district, a large proportion of the buildings consist of mudbrick structures, while in Elbeyli, a significant number of buildings were constructed using earthen materials. Notably, many of these buildings remain in use today, demonstrating the resilience of this construction technique.

Despite its various advantages, including low energy consumption, adaptability, natural composition, cost-effectiveness, and high insulation performance, earthen materials also present some challenges. These include low compressive strength and a high-water absorption rate, which can limit their durability and structural integrity over time. Because of a better understanding and enhancement of the performance of earthen materials, a study was conducted using earth sourced from Iznik, where historical settlements have long relied on earth-based materials. Chemical analyses, including acid loss and ignition loss tests, as well as X-ray diffraction (XRD) analysis, were performed to characterize the raw earth composition. For stabilization, different binders (natural hydraulic lime, air lime, and cement) were used at varying proportions (6%, and 12% of the dry earth weight). The goal was to assess the impact of these additives on the material's mechanical and physical properties. In this scope, fourteen mixtures were prepared. Two distinct curing conditions were employed to simulate real-world drying scenarios: one set of samples was cured in an oven at 30 °C for seven days to mimic sun-drying conditions, while another set was cured under laboratory conditions at 23±2 °C with 40±10% relative humidity. Following the curing process, the samples were evaluated for their mechanical strength and physical characteristics.

The results revealed that natural hydraulic lime significantly enhanced the mechanical performance of earthen materials compared to air lime. However, its effectiveness was still lower than that of cement, which provided the highest strength improvements. Under oven curing conditions, the mechanical properties improved for all additive types and ratios. Even though the mechanical strength of the samples decreased in laboratory curing, higher mechanical strengths were determined compared to oven curing. Stabilizing earthen materials is essential not only for preserving existing heritage structures but also for promoting their use in modern sustainable construction. By improving their mechanical strength and durability, stabilized earthen materials can serve as viable alternatives to conventional construction materials, contributing to environmentally friendly and cost-effective building practices.

Elaboration and study of thermal and mechanical properties of a novel biocomposite based on turkey feather fibers and organic matrix

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Keywords: turkey feathers: physicochemical characterization; mechanical properties

Nature is so expertly designed that it has provided humanity with various materials possessing remarkable properties (mechanical, thermal, dielectric, or acoustic), many of which remain underutilized in terms of their full potential. Today, scientists are increasingly focused on discovering a new, more eco-friendly source of fibers as an alternative to the traditional mineral or synthetic fibers used to reinforce composite matrices. The decision to incorporate feather fibers into composites is not solely based on their intriguing physicochemical and mechanical properties, but also on their environmental benefits and contribution to sustainable development. These two factors must be an integral part of any consideration when creating new materials. Short keratin fibers, derived from natural resources (such as poultry feathers, hair, horns, hooves, human hair, etc.), are gaining increasing attention in composite development due to their light weight, low cost, favorable mechanical properties, and most importantly, their abundance in nature. Rather than viewing these fibers as worthless agricultural waste, their value is now being recognized through the exploitation of their properties and their reuse in various industrial sectors, presenting a significant challenge for scientists. Today, it is widely acknowledged that most research on natural fibers focuses on cellulose fibers derived from renewable plant sources such as reed, flax, wood, sisal, and jute. Currently, there are limited studies on keratin fiber composites, and industrial applications for composites made from these fibers are non-existent. Keratin is a naturally occurring protein widely used by various organisms as a structural component, forming the outer sheath of hair, wool, feathers, nails, and horns in mammals, reptiles, and birds. It serves as a prime example of a fibrous protein.

The aim of this work is to introduce a new material based on animal keratin fibers. The objectives are twofold: i) First, to provide a new method for recycling these fibers, which are abundant in nature but currently underutilized or not used at all; ii) Second, to use fibers that are both eco-friendly and resistant to chemical attacks, while being biodegradable over time, as an alternative to non-degradable synthetic or mineral fibers. To ensure the longevity of these fibers, it is recommended to protect them from moisture and, particularly, from keratophagous pests, necessitating an initial chemical treatment of the surface.

In this study, we present the development of new composites made with an organic resin (unsaturated polyester), incorporating Turkey Feather Fibers (TFF). Mechanical tests, including tensile and three-point bending, were conducted to evaluate the mechanical properties of these new composites with varying fiber contents. Additionally, the thermal conductivity of the materials was measured on plates with dimensions of 300x300x4 mm^3. Finally, the micro-porous structure of the fibers, observed using ESEM, supports the low density of these materials, as confirmed by the picnometer method.

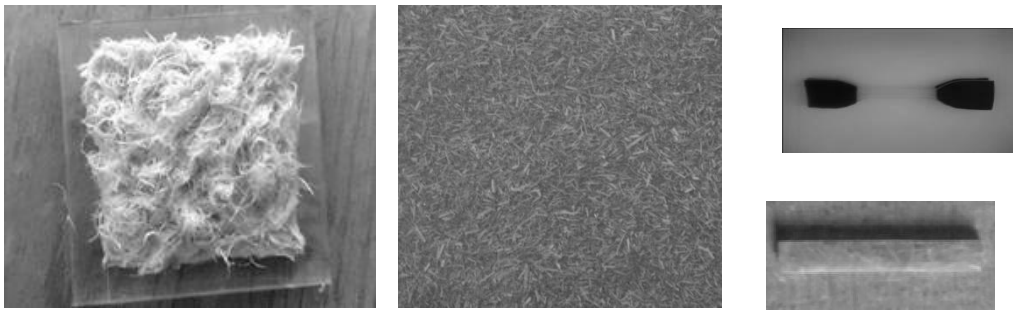

Fig. 1 a) Impregnated fibers turkey feathers b) A plate of composite c) A specimen of tensile test ; d) A test piece of bending test

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Exploring the potential of Australian agricultural and industrial wastes from the source to bio-fabricating viable mycelium-based composites

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Keywords: Mycelium-based composite; Agricultural and industrial waste; Circular economy; Bio-fabrication; Australia.

Australia generates approximately 75.8 million tonnes (Mt) of waste annually, with significant contributions from the agricultural and industrial sectors. Organic waste, particularly biomass, accounts for 14.4 Mt of this total. At the same time, the commercial and industrial sectors contribute an additional 32.8 Mt. A substantial portion of this organic waste—such as sugarcane bagasse, sawdust, mulch, and other plant residues—is either incinerated for energy production (e.g., in sugar mills), discarded into landfills, or left to decompose naturally. These conventional disposal methods represent a loss of potentially valuable material and contribute significantly to atmospheric carbon dioxide (CO_2) emissions, exacerbating climate change. This study investigates the potential of transforming selected agricultural and industrial biomass wastes into mycelium-based composites (MBCs). MBCs are biodegradable materials formed through the growth of fungal mycelium—specifically, the vegetative root-like structure of fungi—on lignocellulosic substrates. These composites offer sustainable alternatives to conventional packaging, construction, and leather materials. The objective of this research was to directly collect underutilised biomass waste streams from Australian factories, farms, and processing facilities and to evaluate their viability as substrates for MBC bio-fabrication. The biomass types selected for this study included hemp hurd, mulch, sugarcane bagasse, coco coir, and Brewer's spent grain (BSG). These were chosen based on their regional availability, cellulose and lignin content, and current disposal practices. Reishi fungus (*Ganoderma steyaertanum*), a locally available fungal species known for its robust mycelial growth, was used as the bio-fabricator in all experimental conditions. In addition to the five biomass types, sawdust sourced from lumber yards and furniture factories was also tested to assess the impact of potential contaminants on mycelial colonisation. The methodology involved substrate preparation (drying, milling, and sterilisation), inoculation with fungal spawn, and incubation under controlled environmental conditions. The resulting MBCs were dried and subjected to mechanical and structural testing upon full colonisation. Compressive strength was measured using a universal testing machine to determine the material's load-bearing capacity, while surface morphology and internal bonding were examined using Scanning Electron Microscopy (SEM).

The results demonstrated that each biomass type yielded MBCs with unique physical properties, largely influenced by their inherent lignocellulosic composition. MBCs derived from mulch exhibited the highest density and compressive strength, suggesting greater suitability for structural applications such as insulation panels or load-bearing packaging. In contrast, MBCs formed from sawdust displayed low strength and brittleness. SEM analysis revealed limited fungal colonisation in these samples, likely due to residual formaldehyde-based adhesives commonly in sawdust from furniture and construction sources. These chemical contaminants inhibited fungal growth and weakened the composite structure. Importantly, the feasibility of fabricating MBCs from bagasse directly sourced from sugar mills opens a new avenue for converting a traditionally low-value fuel into high-value materials. This approach presents a sustainable

alternative to burning bagasse for heat and energy, thereby, creating new markets and reducing associated emissions. By establishing bagasse as a viable feedstock for bio-fabrication, the demand for incineration can be reduced, supporting cleaner industrial practices and diversifying the economic potential of sugar by-products. Notably, the findings highlight the value of mulch—a material often left to decompose or burned, contributing to bushfire risk—as a superior substrate for MBC production. Redirecting this biomass into the fabrication of sustainable materials could offer a twofold benefit: reducing carbon emissions and mitigating fire hazards in rural and peri-urban areas. Additionally, the observed challenges with sawdust emphasise the need for cleaner waste streams and improved sorting practices in industrial recycling processes.

In conclusion, this research demonstrates the feasibility of converting diverse Australian agricultural and industrial wastes into high-performance MBCs through a low-energy, biological process. By leveraging regionally abundant biomass and local fungal species, this study offers a scalable model for sustainable material production aligned with the principles of a circular economy. The successful valorisation of mulch and bagasse into valuable composites could inform both environmental policy and industrial design, fostering innovation in Australia's eco-friendly construction and manufacturing sectors.

Greening concrete with biofilms: Codesigning with nature

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Keywords: concrete, bioreceptivity, biofilm, laboratory test, fluorometry

Building envelopes as artificial rock surfaces are the interface between solid material, biosphere, and the atmospheric environment. They are a natural habitat of subaerial biofilms and can be more or less prone to be colonized (i.e. to be bioreceptive).
While the interaction among organisms and materials has been widely studied for its biodeterioration implications, the targeted increase of the bioreceptivity of building materials is still a new field of research. Focusing on the added value of biofilms on manmade substrates instead of biodeterioration represents a paradigm shift that is long overdue. Accepting nature as part of everyday life represents new aesthetic frontiers and reduces the use of biocides. Moreover, the metabolic processes of photosynthetic biofilms can positively influence human health and life quality in densely populated cities by converting or absorbing pollutants.
In the presented research the bioreceptivity of concrete claddings for building facades is engineered to sustain the natural establishment of microalgae-dominated biofilms. A variety of parameters depending on concrete mixture and surface texture were comparatively analysed using a multi-stage test setup ranging from analysis of samples in petri-dishes combined with a subsequent adhesion test over a semi-controlled conditions step with simulation of weathering conditions in the lab to outdoor weathering. For representative and repeatable testing, a model biofilm of a dual alga/fungus biofilm was developed and successfully implemented in the test strategy. Growth and vitality of the algal component of the biofilms has been assessed with Pulse-amplitude modulation (PAM) fluorometry.
Results from the highly controlled experiments highlight the critical role of pH in both the growth and health of the organisms, with carbonation being crucial for the successful colonization of cementitious materials. Compared to the pH the addition of nutrients only has a minor effect on the bioreceptivity of the tested concretes. In addition, adhesion strength testing suggests that some stress may be beneficial for the organism in terms of increasing resistance to hydrodynamic stress. In the laboratory test with rain simulation, it becomes evident that the surface texture is highly important for the permanent adhesion of organisms and growth is further favored by near surface porosity favoring the retention of water and microorganisms.
The results indicate that a synergistic behavior of algae and fungi is triggered by a certain stress level of the organisms and explain why algal biofilms cultivated under highly favorable lab conditions often fail when exposed to outdoor environmental conditions.
It is evident that a balance between photosynthetic efficiency, growth and biofilm adhesion must be achieved to create an effective and durable algal biofilm green façade system.

Growing mycelium bio composites in arid region and investigating fabrication factors: spawn percent, time intervals and density

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Keywords: Mycelium materials, Circular Economy, Sustainable Building Materials, Agricultural Waste, Thermal Insulation.

As the climate crisis intensifies and the average temperatures rise, it emphasizes that the challenge of our era is to turn our society, and specifically our industry, into a sustainable one. To achieve this, the economy should become circular, where byproducts of one industry becomes the raw materials of another, rather than the current linear model where waste accumulates, and resource depletion intensifies. The construction sector is particularly intensive, with about 40% of the energy produced annually going to manufacturing construction materials, constructing buildings, and mainly maintaining comfortable temperature inside them. Mycelium based materials hold promising potential to facilitate this transition, as they are based on agricultural waste bonded by fungal mycelium, grown at room temperature. The material's properties point it can be implemented as an insulating material, with thermal conductivity as low as commercial insulation materials (0.03-0.04 W m^{-1} K^{-1}).

As mycelium materials have been grown mainly in temperate climates to this point, this study focused on growing them in arid regions, using date palm agricultural waste as a main substrate, mixed with grapevine pruning and spent coffee grounds. To do so, a fungus species was chosen based on its growth rate on a date-palm-grapevine mix. Using the chosen species, a preferred ratio of the three ingredients was selected based on thermal conductivity and compression properties, while using a 21-day fabrication process with 3 stages (bag, mold, ripening). In order to shorten the fabrication time, different time intervals of the process stages were investigated, along with the amount of spawn for inoculation. Fourteen conditions with overall fabrication times ranging from 21 to 7 days were examined. Later, the effect of material density on compression and thermal properties was measured. Samples with five different densities were made by applying different force in the molding stage, while keeping the same composition and 10-day fabrication process.

The paper offers a structural methodology to develop a new substrate mix based on local wastes, from the stage of choosing a fungus species, through the ratio of ingredients, to the reduction of the overall process time. The results showed that mycelium materials can be grown in arid regions, even within a 7-days fabrication process, much shorter than the 12-24 days previously demonstrated. This is a significant finding that shows the feasibility of industrializing the process. Using the same substrate and fabrication method, but with different densities at the molding stage, yielded thermal conductivity values in the range of 0.027 to 0.052 W m^{-1} K^{-1} and compression strength values in the range of 0.01 to 0.09 MPa. The relationship between density and thermal conductivity is linear, while compression is related to density by a power function. This shows that the final properties can be tuned by the density of the material, which can be easily controlled at the molding stage.

Integrating mycelium materials in the construction sector as an insulating material can contribute both to reducing the CO_2 emissions of the building itself, since the material is carbon negative, as well as to

improving the energy efficiency of the building by enhancing the thermal function. Overall, it can help drive the construction industry towards greater sustainability.

Improving the lifespan of mycelium bio-composites

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The MycEoLA project investigates the lifespan of mycelium bio-composites (MBCs) used in construction to assess their durability and structural integrity under various environmental conditions. As biobased materials gain prominence, understanding their longevity is critical for industry adoption. MBCs offer a sustainable alternative to conventional building materials, but their long-term performance in real-world conditions remains insufficiently explored. This study aims to quantify their lifespan through controlled aging experiment combined with material characterization. In addition, the project investigates multiple strategies to extend the lifespan of MBCs via natural coatings.

Artificial aging methods are employed to simulate prolonged environmental exposure. MBC foams and boards were subjected to a pre-test using water boxes at 20℃ ± 3℃ and 90% relative humidity (RH) ± 5% RH, to then be tested using climate chambers at three different conditions: mild – 15℃ ± 3℃ and 40% RH ± 5% RH), extreme - 30℃ ± 3℃ and 80% RH ± 5% RH and intervals - 15 ℃ ± 10℃ and 60% RH ± 20% RH. Natural coatings produced from varying concentrations of citric acid, acetic acid, tea tree oil, orange oil, oregano oil, tung oil and Impershield coating were applied to the MBC foams with the intention of improving the lifespan of the materials.

Digital Image Correlation (DIC) is utilized to track surface changes over time, while microstructural analysis provides insights into the effects of environmental exposure on material integrity. Mechanical, sound absorption, hydrophobicity and flame propagation testing are conducted before and after aging intervals to assess material performance over time. Thermal conductivity measurements reveal that aging affects the insulating properties of MBCs. Chemical composition analyses using Fourier Transform Infrared Spectroscopy (FTIR) highlight compositional shifts associated with the use of coatings and prolonged exposure.

Preliminary results indicate that unmodified MBCs exhibit significant structural degradation within a 12-month period, while those incorporating stabilizing treatments display enhanced resistance to environmental stressors. Preliminary findings suggest that incorporating hydrophobic treatments significantly reduces moisture absorption, mitigating microbial regrowth and structural degradation. Samples using 60% tea tree oil and oregano oil significantly improve the lifespan of the material, with all samples outlasting the pre-testing experimental time of 147 days. Initial findings suggest that while untreated MBCs experience a progressive decline in strength, modified formulations maintain mechanical integrity for longer durations.

Although these results provide valuable preliminary insights, full-scale lifespan assessments are ongoing, with comprehensive data expected by July 2025. Through establishing a robust understanding of MBC lifespan, this research aims to support their integration into sustainable construction practices, promoting wider adoption in the industry. The lifespan analysis within MycEoLA demonstrates that MBCs have potential as sustainable construction

materials but face challenges regarding longevity and degradation. While modified MBCs perform better than untreated ones, environmental conditions greatly influence material stability. Strategies such as optimized post-treatment and environmental exposure management can enhance their lifespan. Future research should focus on refining protective treatments and quantifying real-world application scenarios for broader industry integration.

Influence of various Biomass Ashes on the Mechanical Properties, Microstructure and Leaching Behaviour of Extruded Fired Clay Bricks

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Keywords: biomass ash, extruded fired clay bricks, ceramic-technological tests, microstructure, leaching

Nowadays, biomass is gradually replacing fossil fuels in thermal and combined heat and power plants, which consequently produce ever larger quantities of biomass ash. Therefore, new strategies for ash management must be explored to avoid ash landfilling. As thermal treatment reduces the leaching potential of ash, the incorporation of ash into fired clay bricks appears to be a promising solution for its safe management. This study investigates the potential of eight different biomass ashes, collected within the EU project AshCycle - *Integration of underutilized ashes into material cycles by Industry-Urban symbiosis,* for use in the production of fired extruded clay bricks. The influence of ash content on the microstructure of fired bricks was investigated for 0, 5, 10 and 15 mass percent (ma%) of selected ashes, resulting in the highest compressive strengths of the bricks. In addition, the influence of ash type on the microstructure of fired bricks was investigated for mixtures with 10 ma% of the investigated ashes.

The brick base mixture in this study consisted of marl (50 ma%), illite-chlorite clay (48 ma%) and coal (2 ma%). Different biomass ashes were investigated: (i) woodchips (W) fly ash (FA) and bottom ash (BA), (ii) FA and BA from co-combustion of woodchips and lignite (BC-W), (iii) FA and BA from co-combustion of municipal solid waste (light fraction) and dehydrated sewage sludge (MSW-SS), (iiii) FA from the co-combustion of lignite, wood residues, bark and fibrous sludge from the deinking process and the wastewater treatment plant (BC-W-PS), (iiiii) mixed FA (20%) and BA (80%) from wood residues, bark and fibrous sludge from the deinking process and the wastewater treatment plant (W-PS). BC-W ashes had the highest SiO_2 content, according to quartz content which was similar in FA and BA. FA had the highest Fe_2O_3 content of all ashes, which was due to hematite and brownmillerite, while BA had the highest MgO content, which was due to periclase. The composition of MSW-SS and varied significantly between FA and BA. FA had high Na_2O and Cl content, which was due to halite, while BA had high Al_2O_3 content, which was due to calcium aluminate phases. The ashes of W-PS and BC-W-PS had the highest CaO content attributable to calcite and lime, while BA contained about 30 ma% more CaO than FA.

Ashes were sieved so that they passed through a sieve with a mesh size of 1 mm, and only the fraction bellow 1 mm was incorporated into the raw brick mixtures. The chemical composition of the clay base mix

and the ashes was determined by X-ray fluorescence spectrometry (XRF), the mineral composition by X-ray powder diffraction (XRD) and the particle size distribution by laser diffraction granulometry. The samples for the ceramic-technological tests were produced by vacuum extrusion. The properties of the mixtures produced were determined during shaping (plasticity according to Pfefferkorn, moisture), drying (drying shrinkage) and firing (firing shrinkage, density). The effect of the firing temperature on shrinkage and water absorption was investigated by firing in a gradient kiln in combination with a water absorption test. The bricks for the ceramic-technological tests were fired at 950°C. The tests included the determination of compressive and bending strength, drying and firing shrinkage, density and water absorption. The effect of ash content and ash type on the mineralogy and microstructure of the bricks was investigated using quantitative X-ray diffraction (QXRD), mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM), and energy dispersion spectroscopy (EDXS). The SEM examination was carried out in two directions, parallel and perpendicular to the extrusion. The leaching tests were carried out in accordance with standard EN 12457-2:2002 on brick particles smaller than 4 mm.

The results showed that the compressive strength of the bricks gradually decreased with increasing ash content, as the ash reduced the plasticity of the brick mix, which therefore required higher water content, resulting in higher drying shrinkage and cracking. However, except for the brick with 5 ma% paper sludge ash, all samples had a compressive strength above the limit of 10 MPa specified in the EN 772-1 standard and are suitable for use in construction. The main crystal phases of the bricks were quartz, plagioclase, K-feldspar and hematite. The amorphous content of the bricks was related to the unreacted, decomposed clay minerals and did not influence the compressive strength. The microstructural relationships are discussed in detail and a crack model is proposed. The leaching results confirmed that all bricks can be classified as non-hazardous material. The study promotes the recycling of waste ash in the brick industry by providing a comprehensive unified experimental and theoretical basis for understanding the relationships between the chemical and mineralogical properties of ash on the one hand and the physical, mechanical, microstructural, and environmental properties of extruded fired bricks with various biomass ashes on the other.

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Investigating the Influence of Hemp Shiv Size on Air Lime-Based Mortars for Sustainable Restoration Applications

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Keywords: Air lime, hemp shiv, grinding, mechanical strength, thermal conductivity

1. Introduction

Lime mortars are preferred in conservation work for their compatibility with heritage buildings. However, enhancing the performance of lime mortars while maintaining their compatibility and sustainability remains a challenge. The incorporation of natural reinforcements, such as hemp, specifically its woody core known as hemp shiv (a by-product of hemp fibre harvesting) offers a promising solution. Characterized by low density, low thermal conductivity, and high-water absorption capacity, hemp shiv is advantageous for sustainable construction applications.

This study evaluates the effects of hemp shiv sizes as reinforcement in air lime-based mortars for restoration. Unlike their widespread use in hempcrete, in this study hemp shives are used in smaller quantities similar to the incorporation of fibres into mortars, facilitating targeted improvements in mechanical strength, thermal properties, and workability without significantly altering mortar's density or texture.

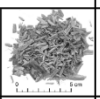
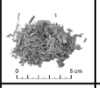
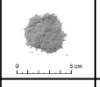
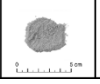
2. Materials and Methods

Air lime-based mortars were prepared with the addition of pozzolanic agents and hemp shives of various sizes (Table 1). Calcitic air lime (CL-90) served as the binder, with standard silica sand as the aggregate at 1:3 binder to aggregate ratio. To enhance mechanical properties, pozzolanic agents such as silica fume and volcanic ash were incorporated at 15% by weight of the air lime. Hemp shives, both raw and ground for 15 seconds, 1 minute and 2 minutes, using a ball grinding mill, were added as reinforcement at 1% by weight of air lime. The water to dry mixture ratio was consistently maintained at 25%.

Materials for each mix were first dry blended to achieve a homogeneous mixture, followed by the addition of water and stirring at low speed for 90 seconds to ensure uniform consistency. Fresh mortar samples were cast in cylindrical moulds and stored under controlled laboratory conditions (20°C ± 0.5°C, 45% ± 5% RH).

Tests on fresh mixtures included fluidity (flow table test, UNE-EN 1015-3 standard) and water retention (UNE-EN 83-816-93 standard). Porosity after 28 days of curing was analysed using mercury intrusion porosimetry (MIP) with pressures ranging from 0.0015 to 207 MPa. Compressive strength was tested at 7 and 28 days, and thermal conductivity was measured across a 10°C temperature gradient between two controlled plaques at average temperatures of 5, 15, 25, and 35°C.

Table 1. Mixture design, and fluidity, water retention, porosity and compressive strength results

Sample		Hemp Type		Fluidity (mm)	Water Retention (%)	Porosity (%)	Compressive Strength (MPa)	
							7th days	28th days
Air lime + Silica Fume (15%) + Volcanic Ash (15%) + Hemp (1%)	A0	Without Hemp		185	94.24	34.52	0.35 ± 0.09	0.51 ± 0.01
	AR	Raw		188	91.83	31.73	0.23 ± 0.02	0.52 ± 0.05
	AG1	Grinded 15 sec		171	95.35	38.94	0.19 ± 0.03	0.62 ± 0.08
	AG2	Grinded 1 min		190	95.84	36.66	0.15 ± 0.02	0.93 ± 0.06
	AG3	Grinded 2 min		201	96.10	41.91	0.20 ± 0.02	0.45 ± 0.02

3. Results

3.1. Fresh State Analyses

Table 1 shows that the addition of hemp increased the fluidity of the mortars compared to the reference, except for AG1. The slump values increased with decreased hemp size, likely due to the grinding process altering the porous structure of the shives, resulting in a more rounded shape that reduces friction and enhances the ball-bearing effect.
Water retention was high (>90%) across all mortars. Although raw hemp shiv reduced water retention, longer grinding times improved it, indicating particle size's key role.

3.2. Hardened State Analyses

Porosity ranged between 31.7–41.9% (Table 1). Grinding hemp increased porosity due to disruption of mortar homogeneity and weak bond formation between the binder and the hemp shiv. Pore size distribution curves (Figure 1a) revealed that increasing hemp grinding time resulted in larger pore diameters, particularly noticeable for AG3.
The compressive strength was initially low, while AG1 and AG2 exhibited higher strength than the reference on the 28th day, AG3 containing finer hemp shives, showed reduced strength development. The porosity of these samples correlated with their compressive strength; the lower the porosity, the higher the compressive strength.
Thermal conductivity (λ) findings (Figure 1b) revealed a 20% reduction in AG2 compared to A0, suggesting that while hemp generally reduces thermal conductivity, the size of the hemp shiv plays a significant role.

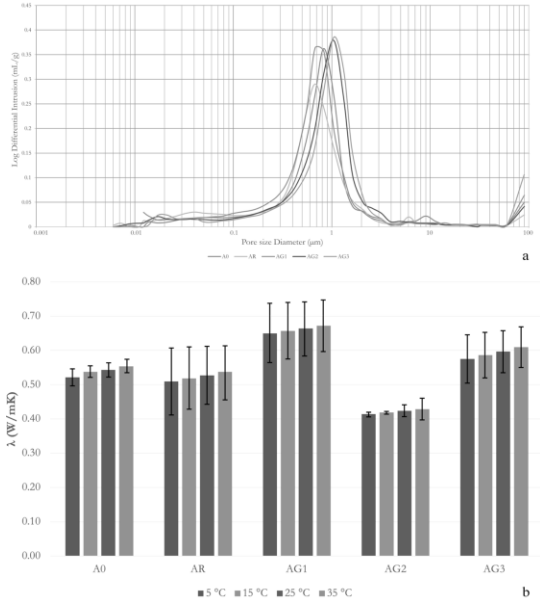


Figure 1. (a) Pore size distribution determined by MIP, (b)Thermal conductivity at the average temperatures of 5, 15, 25, 35°C

4. Conclusion

The incorporation of ground hemp shiv into lime-based mortars presents both advantages and challenges. While smaller hemp shiv sizes improved fluidity and water retention, they also increased porosity, influencing compressive strength and thermal conductivity. Moderate grinding (e.g., AG2) appears to offer the best balance between workability, mechanical performance, and thermal efficiency, making it a promising alternative for sustainable restoration applications.

5. Acknowledgement

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Investigation of the use of rice husk ash as a supplementary cementitious material in concrete: a case study of the bangladeshi rice husks

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Keywords: Rice husk; Cement; Concrete; Strength; Cost analysis.

ABSTRACT

Concrete is the second most consumed material in the world, after water, with cement being a key ingredient in its production. Without cement we cannot think about making of concrete. As concrete is integral to modern infrastructure, it is essential to assess its environmental impact and sustainability, especially in light of the growing global consumption of concrete. This paper investigates the potential of Rice Husk Ash (RHA) as a supplementary material for cement in concrete to address the challenges of resource availability, environmental concerns, and economic feasibility. The study demonstrates that replacing a portion of cement with RHA can achieve up to 90% of the strength of conventional cement-based concrete. Furthermore, cost analysis shows that substituting RHA in quantities ranging from 5% to 20% can result in cost savings of 3% to 10%. These findings highlight the potential of RHA as a sustainable and cost-effective alternative in concrete production.

INTRODUCTION

Presently, various supplementary cementitious materials are added to cement to enhance the properties of concrete and reduce the increasing consumption of cement. Fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans, such as Calcined Shale, Calcined Clay and metakaolin are some examples of the most commonly used supplementary cementitious materials around the globe. Typically, these materials, when used in conjunction with Portland or blended hydraulic cement, contribute to the properties of hardened concrete through pozzolanic activity[1, 2]. Incorporating SCMs in concrete production not only improves the quality of concrete, but also plays an important role in reducing the cost of cement. Today, the high cost of cement is forcing the construction industry to look for alternative and cost-efficient cementitious materials, one of these potentials is the utilization of locally available cementitious materials from industrial and agricultural wastes such as rice husk. Various studies have indicated the use of ashes from rice husk reduces the overall cost of concrete and improves the quality and performance of concrete at the same time[3, 4]. Previous studies have shown that rice husk burned into ashes referred as rice husk ash (RHA) has a potential to replace cement between 10%-30% by weight, enhancing compressive strength, chloride ion resistance and alkali silica reactivity[5, 6, 7, 8]. However, the high cost of construction materials and low quality work are the major challenges associated with the industry. Currently, one bag (50 kg) of OPC is purchased at BDT 550 ($4.50) which showed more than 92% increase from 2006 which was BDT 235 ($1.93). One way of addressing this high cost of materials like cement is to utilize locally available cementitious materials from agricultural wastes such as rice husk. Although the use of rice husk ash has been previously used in concrete making, the production and quality of rice husk ash depends on various factors such as fineness, geographic location, crop year and burning conditions; temperature, heating rate, and duration[9].

RESEARCH SIGNIFICANCE

Environmental issues presently are given a great emphasis by several countries worldwide. Bangladesh, whose economy largely depends on agriculture, is one of the rice growing countries in Asia with an estimated 10.50 million hectares of land, where the by-product or rice husk is normally disposed of as waste creating threat to the environment such as releasing a large amount of dark smoke to the atmosphere when in contact with fire and causing a bad smell especially when there is moisture in it.

This study investigates the properties of RHA to address the increasing cement cost through the introduction of an alternative pozzolanic material in concrete production in construction industry of Bangladesh as well as Western Asia.

EXPERIMENTAL INVESTIGATION

The rice husk used in the present investigation was collected from Dinajpur district. The husk was burnt in a muffle furnace at a 550^0 C-650^0 C for 6 hours and then allowed to cool inside the furnace for about 24 hours. Finally, the husk was grounded to the required size using ultra-centrifugal mill, then the Rice Husk Ash was sieved by 75 μm ASTM sieve in order to remove larger size particles.

Once the husk is burnt, it is turned into Whitish-Grey color. This Whitish-Grey color means the husk is completely burned with a lower carbon content. The fact that the Rice husk has turned into Gray when grinded proves that the Rice husk meets the physical (color) requirement as reported by various researchers.

Materials

The key component of this study is the RHA. **Table 1** shows the chemical analysis of RHA. Based on Table 1, the sum of SiO_2, Al_2O_3 and Fe_2O_3 is 92.76%, which surpasses the value of 70%, set by ASTM C618 for pozzolanic materials. The Low value of 2.89% also complies with the ASTM standard, which sets the maximum value of 3% and 10% respectively[10, 11]. **Fig. 1.** Will clarify the procedure for preparation of RHA.

CEM type I (OPC cement) was used. Physical properties of the cement are summarized in **Table 2**.

Bholagonj boulder coarse aggregate was used as coarse aggregate for making concrete. The maximum size of the aggregate was 20 mm (0.79 in.). The aggregate grading was controlled as per ASTM C33. Sylhet sand (River sand) was selected as fine aggregate. The gradation curve of particle size distribution both for the coarse aggregate and the fine aggregate are shown in **Fig. 2** and **Fig. 3.** Different physical properties of the coarse and fine aggregates are summarized in **Table 3**.

Portable deep tube-well water was used for preparation of concrete.

Specimens

Plain cylinder specimens of diameter 4 in. (101.6 mm) and length 8 in. (203.2 mm) were investigated. C-25 mix design was selected with the use of five different percentages of RHA in concrete mixture. 0%, 5%, 10%, 15% and 20% of RHA by weight of cement were mixed to prepare the concrete specimens. The mixture containing 0% RHA that is completely cement concrete is referred to as control mixture in this study. Air content was assumed to be 2% of concrete volume. In **Table 6** the mixture proportions by weight and cost analysis are summarized. Mix design was adapted from ACI 211.1 and ACI 318 Hover (1995).

Items of investigation

At the age of 7, 28 and 90 days of curing under water, plain concrete specimens were tested for compressive strength. All the specimens were also checked for setting time, temperature and developed crack patters during hardening. A detailed estimation of cost for each specimen has also investigated for analyzing the cost effectiveness.

ANALYTICAL INVESTIGATION

Compressive strength is one of the most important engineering properties of concrete. It is a standard industrial practice that the concrete is classified based on grades. This grade is nothing but the Compressive Strength of the concrete cube or cylinder. In this study Cylinder samples were tested under a compression testing machine to obtain the compressive strength of concrete. The compressive strength obtained from the Cylinder Crushing Machine is based on:

$$\sigma = F/A \ldots (\mathrm{N/mm^2}) \quad (1)$$

Where

$\sigma =$ The cylinder strength of concrete

F $=$ Applied load

$A = \pi r^2$ … (mm²); Cross-sectional area of the cylinder with radius r (2)

EXPERIMENTAL RESULTS AND DISCUSSION

Compressive strength variation with percent replacement of RHA

The obtained values of concrete compressive strength according to the different used percentage of RHA with cement content are shown in **Table 4.** With the increase in percent amount of RHA, a gradual increase in compressive strength has been observed in case of 90 days of curing under water. The highest value of compressive strength has been obtained for the specimen containing 20% RHA with cement content. An increment of 2.56% in strength gaining is possible with respect to 0% RHA containing specimen (control mixture). In case of 7 days and 28 days curing specimens, a little fluctuation in strength gaining has been observed. **Fig. 4** show the variation in strength gaining (%) with RHA replacement measured in percentage for each type of curing.

Temperature and setting time variation

Table 5 shows the generated temperature and required initial and final setting time for each of the specimen. The general observations from the results show that rice husk ash retards the time taken to attain the peak temperature during the temperature condition. This also confirms the result obtained from the setting time of cement pastes.

Physical Investigation of crack formation

Only the physical measurement for crack formation were done. Crack developed in control mixture was significant with respect to RHA replaced mixtures. With the increase in percent replacement of RHA in concrete the crack formations were found become minor. **Table 5** shows the physical measurements for crack development with temperature and setting time. **Fig. 5** illustrates the real photographs of formed cracks.

Cost Analysis

One of the major advantages of using rice husk ash in concrete is its economic benefit. Even though it is difficult to determine the burning and grinding cost of manufacturing of RHA, considering the material costs for 1m³ C-25 concrete sample it has been observed that 3% to 10% cost saving is possible in a replacement between 5% to 20%. A detailed estimation of cost and materials proportions are shown in **Table 6**.

FURTHER RESEARCH

The study represented here is only a part of a mammoth research working. Further research can be continued by investigating the behavior of RHA replaced concrete mixed with different admixtures. Water penetration in concrete is also an important parameter to measure for durability check. So, this research can be elongated based on this parameter. Investigating the behavior of RHA concrete in reinforced concrete members can open a new chapter for this study. Level of corrosion in reinforced concrete, chloride and Sulphate penetration and so many case studies are possible based on this RHA replaced concrete. The results of such studies would directly benefit the construction industry as well as sustainability of construction materials specially in this rapidly growing world.

CONCLUSIONS

Based on the above study, the following conclusions are drawn:

The Bangladeshi rice husk burnt at 550^0C-650^0C for 6 hours yields a good pozzolanic property for use as a supplementary cementitious material in concrete. It can be directly used to make PCC or blended cement.

By reducing cement quantity used in concrete, this study indirectly indicates the reduction in CO_2 generation during cement production. It also reduces heat of hydration and temperature in concrete.

Incorporation of rice husk ash in concrete results in increasing the concrete durability, long term compressive strength, prevention of thermal crack and production of cost-effective concrete.

Investigation the strength of compressed stabilized earth bricks (CSEBs) as a green construction material

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Keywords: Clay Soil, CSEB, Sustainable Material, CO_2, compressive Strength, Low Emission

Cement is among the top five most consumed products on earth. Manufacturing of cement produced about 6% of the total carbon dioxide (CO_2) produced worldwide. It is estimated that manufacturing of cement reached about 4.9 billion tons in 2022. In addition to that, the construction sector consumed around 30% of the international energy consumption. It is expected at this rate of human activity, the global temperature increases 1.5 Co by year 2046. This huge production already started in creating many environmental problems such as climate changes, acidic of ocean, and rising the global temperature. Therefore, it is vital to integrate alternative materials strong enough to be used in building construction with low CO_2 emissions and less energy consumption in order to reduce the negative impact of such hazard materials on our environment and planet. Earthen natural material is a good potential to replace concrete and fired bricks materials. This research investigates the compressive strength of compressed stabilized earth bricks (CSEB) as a green construction environmental friendly material for potential use in construction industry. The CSEB is made from natural clay and sand with low percentages of cement. In this research, sand and clay soils were brought to the geotechnical laboratory at Minnesota State University. The physical properties of sand and clay were determined in accordance with American Standard for Testing and Material (ASTM) standard specification. CSEBs specimens were prepared with different mixtures of sand, clay, and cement at 15 MPa compaction pressure and tested under dry and saturated conditions. In addition to that, the sand and clay and cement were mixed with Nano-Silica materials at three different percentages 0.5%, 1.0%, and 1.5% by the dry weight of the mixture. The specimens were compressed with 15 MPa compaction pressure into 250 mm x 125 mm x 100 mm solid mould to form CSEBs. After preparing the specimens, they were placed in room temperature and allowed to cured and hardened. The curing process is performed by spraying CSEBs specimens by water on daily basis. Then specimens were tested after 7 days, 14 days, and 28 days from the time of preparation. The test results showed that the curing time increased significantly the compressive strength of the CSEBs and the dry condition gives better results than saturated conditions in term of compressive strength. Additionally, the test results showed that the addition of 0.5% of Nano-Silica will enhance the compression strength at the combination of 60% sand, 40% clay, and up to 10% cement content. Higher percentages of Nano-Silica material more than 1.0% will cut back in the strength value. The findings of this research will contribute substantially to saving energy and reducing CO_2 emission generated from the production of cement. The findings imply that CSEBs can be used as a green low coast material and can replace the conventional method of using cement and fired earth bricks in building construction. Many other advantages encourage the use of the CSEBs in the construction sector such as it easy to manufacture, can be prepared in the construction site with no transportation coast, fire resistance, no high skills labour are needed and good thermal properties.

Marine bio-colonization performance of seawater / sea sand concrete prepared with incorporation of solid wastes

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Keywords: Low-pH concrete; Seawater; Sea sand; Waste glass powder (GWP); Marine biodiversity

In this study, low-pH concrete mixes were designed and prepared with seawater, sea sand, and locally sourced solid wastes including waste glass powder and incineration sewage sludge ash. Concrete mixes were then characterized by carrying out an extensive programme of experimental works including compressive strength, surface pH, chemical composition, and heavy metal leaching. The bio-colonization performance of eco-concrete tiles was evaluated based on experimental results and site monitoring. The experimental results indicated waste glass powder contributed towards strength development compared to the use of incineration sewage sludge ash. Portlandite present in conventional concrete which contributed to concrete pH values of above 12.5 was reduced by using solid wastes in low-pH concrete mixes. In an early marine exposure age within 1 month, the low-pH concrete prepared with waste glass powder and incineration sewage sludge ash enhanced the growth of marine species. However, this promotion effect became unobvious with further marine exposure periods of marine immersion.

Prediction of Compressive Strength of Compressed Earth Block (CEB) Walls from the Unit Strength

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Keywords: Building materials, compressed earth blocks, compressive strength, standards and codes, sustainability.

Construction with earth uses ancient techniques to provide a sustainable building solution to substitute common industrial building materials. A modern form of earthen building system is the compressed earth block (CEB), a compacted earth masonry unit. Stabilized CEBs are soil compressed with additives (lime, cement, and other stabilizers) to enhance the quality of the block. CEB has already been employed for house construction in multiple areas worldwide. CEB has proven its advantages, from thermal conductivity, mechanical characteristics, and a high sustainability profile. However, its standing as a building material in the construction industry does not reflect these qualities, showcasing an underutilization. Implementing CEB has potential significance in furthering the development of wide-scale affordable housing, offering a hopeful future for sustainable construction.

Extensive research has been done worldwide on the performance of CEB at the material level. However, less attention has been paid to the structural design of CEB buildings. One of the barriers to the large-scale use of CEBs in construction is the lack of adequate standards with detailed provisions for designing structures and buildings made with CEBs. Most of the standards focus on the manufacturing and testing the CEB units. Furthermore, most current CEB standards disagree on some fundamental design aspects. CEB standards disagree with the test procedures for determining the most important mechanical properties and compressive strength. It is well known that the ratio of a masonry wall height to its thickness (h/t) is a crucial factor influencing its compressive strength. The effect of h/t is reflected in various concrete masonry codes through correction factors to convert the compressive strength calculated for units or small assemblies (prisms) to the compressive strength of walls (with standard h/t). It is worth mentioning that the current CEB standards do not have explicit provisions to convert the unit CEB compressive strength to the compressive strength of the CEB walls, which is a significant concern.

A large database of compressive tests on stabilized CEB masonry units, assemblies (prisms), and walls reported in the literature over the past three decades was assembled and analysed to develop accurate and simple formulae to predict the compressive strength of stabilized CEB walls from the unit strength. Eighty-five average compressive test results, representing 260 individual tests, were compiled into this database. A thorough critical review of the database was conducted to evaluate the effects of different factors on the compressive strength of stabilized CEB. The collected database was statistically analysed to derive an accurate empirical formula to estimate the compressive strength of stabilized CEB walls from the unit strength. The predictive capability of the formulae proposed was compared to the existing empirical equations, and it was found to produce the most accurate predictions of the compressive strength of stabilized CEB masonry walls with the least variation.

The proposed formula can be utilized in CEB design codes, contributing to solving the lack of standardization, which is the most significant barrier to the large-scale implementation of CEB. This effort can help advance the effective use of CEB masonry as a competitive building material.

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Research on the Mechanism and Environmental Benefits of Biofilm-Modified Gypsum Composites in Construction Materials

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Keywords: Gypsum, Retarder, Setting Time, Biofilm, Functional Mechanism

As a widely utilized cementitious material, performance optimization of gypsum has remained a focal point in construction materials research. With the global emphasis on environmental protection and sustainable development, in-depth investigations into gypsum-based materials have gained heightened significance. As a widely utilized calcium sulfate mineral, gypsum is extensively employed in building material production due to its exceptional plasticity and ease of processing. Additionally, gypsum serves as a retarder, expanding agent, and additive in cement formulations, effectively delaying cement hydration, enhancing concrete durability and structural integrity, and improving flow characteristics. However, conventional gypsum materials exhibit significant limitations. For instance, their rapid setting time poses challenges during construction, such as restricted working windows and potential compromises in construction quality. If not promptly utilized, fast-setting gypsum slurries may rapidly transition into a hardened state, leading to material waste and increased costs. This study focuses on elucidating the functional mechanisms of biofilms within gypsum systems. Conventional engineering practices predominantly employ chemical retarders, which not only exacerbate CO_2 emissions throughout their lifecycle but also release volatile organic compounds (VOCs), posing substantial risks to human health and ecosystems. In contrast, algae-derived biofilms present a carbon-negative alternative due to their photosynthetic capability to sequester atmospheric CO_2 during growth. Furthermore, biofilm production from cultivated bacteria offers operational simplicity and reduced energy consumption compared to energy-intensive conventional retarder manufacturing processes. These attributes confer significant environmental advantages to biofilms as sustainable gypsum retarders. Experimental results demonstrate that biofilm-modified gypsum exhibits notable retarding effects. At a 5 wt.% biofilm dosage, the setting time of gypsum is extended by 3300 minutes, primarily attributed to biofilm-induced inhibition of crystal growth and altered hydration reaction kinetics. This prolonged setting window enhances operational flexibility during construction, thereby improving formwork quality and workability. Rheological investigations reveal that biofilm incorporation elevates the yield stress and viscosity of gypsum pastes. Mechanistic studies employing Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), and scanning electron microscopy (SEM) elucidate the retardation mechanisms and microstructural evolution of hydration products. At the microscale, biofilms modulate interparticle interactions and paste structural development, leading to distinct rheological behaviors during flow and plastic deformation. These findings provide critical insights for optimizing molding processes, enhancing mechanical properties, and improving the constructability of gypsum-based products. Life cycle assessment (LCA) quantifies the carbon sequestration potential of biofilms in comparison to traditional chemical retarders. Results highlight the unique carbon fixation capacity of biofilms, which mitigates CO_2 emissions over the gypsum lifecycle. This carbon capture mechanism not only reduces environmental burdens but also advances the development of low-carbon construction materials, offering innovative pathways for sustainable applications in the building sector. In conclusion, this study systematically elucidates the multifunctional roles of biofilms in gypsum systems, including retarding effects, carbon fixation, and rheological modification. These findings enrich the theoretical framework of gypsum materials while providing robust technical support for designing high-performance, eco-friendly gypsum-based composites. The proposed strategy holds

promising potential for broad applications in construction, mold manufacturing, and related fields, thereby accelerating the sustainable transformation of the gypsum industry.

Sustainable Bio-based Concrete for Green Infrastructure: Improving Water and Nutrient Supply for Vegetation Growth

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Keywords: Bio-based material, Water retention capacity, Plant growth, Bio-based concrete, Ecological concrete

The development of sustainable construction materials that contribute to environmental restoration and green infrastructure is a priority in the field of civil engineering. Porous ecological concrete, known for its role in promoting water infiltration and plant growth, has become an essential material in urban landscaping and vegetation restoration. However, traditional porous concrete often suffers from limited water retention and nutrient supply, which negatively affects plant growth and vegetation health. To overcome these limitations, the incorporation of bio-based aggregates has been proposed as a promising approach to enhance the performance of porous concrete in supporting plant life. This study investigates the use of heat-treated kernel peach shells as bio-based aggregates in porous concrete, aiming to improve its water retention and fertilizer storage capacity, thereby promoting plant growth.

In this work, bio-based porous concrete was developed by incorporating heat-treated kernel peach shell as the coarse aggregate. The physical and mechanical properties of the resulting concrete were assessed using standard testing methods, including compressive strength, water absorption, and porosity measurements. To evaluate the effectiveness of the concrete for plant growth, a series of plant growth experiments were conducted with two types of vegetation: Festuca arundinacea (a grass species) and Amorpha fruticosa (a shrub species). The concrete samples were pre-soaked in a nutrient solution to investigate the interaction between the bio-based concrete and plant growth. The water retention and fertilizer release capabilities of the bio-aggregates were assessed by measuring the uptake and release of nutrients over time. Additionally, plant growth parameters, including height, biomass, and overall health, were recorded and compared with those grown in conventional concrete.

The results showed that bio-based porous concrete exhibited significant improvements in water retention and nutrient release compared to conventional reference concrete. The water absorption of the bio-based concrete increased by 325-479% after 72 h, demonstrating its enhanced capacity for moisture retention. Additionally, the use of bio-aggregates improved the concrete's ability to store and release nutrients, which in turn supported better plant growth. Both Festuca arundinacea and Amorpha fruticosa demonstrated enhanced growth in bio-based concrete compared to the reference concrete, with plants growing taller and healthier. In particular, the bio-based porous concrete supported the development of plant roots and foliage throughout four seasons, indicating its potential for year-round application in ecological restoration projects. Furthermore, nutrient solution soaking method further enhanced the growth performance of the plants, highlighting the synergistic effects of bio-aggregates and nutrient availability on plant health.

The findings of this study highlight the importance of selecting appropriate aggregates for improving the sustainability and functionality of porous concrete in ecological applications. The heat-treated kernel peach shells, when used as bio-aggregates, significantly enhance the concrete's water retention and nutrient release

capabilities, making it more suitable for plant growth. The increased water absorption capacity allows for better moisture availability, especially during dry periods, which is critical for the survival of plants in urban and rural landscapes. Additionally, the improved nutrient release properties of the bio-based concrete contribute to the enhanced growth of both grass and shrub species. These results suggest that bio-based aggregates not only improve the physical properties of porous concrete but also support the long-term health of vegetation, contributing to the overall sustainability of urban ecosystems.

This study demonstrates the potential of bio-based porous concrete, incorporating heat-treated kernel peach shells as aggregates, to significantly enhance water retention and nutrient release for plant growth. The findings suggest that such bio-based concrete can serve as a sustainable material for ecological restoration and green infrastructure projects, promoting healthier vegetation in urban environments. The use of nutrient solution soaking method further boosts the performance of the concrete, indicating its versatility and potential for diverse applications. Future research should explore the optimization of bio-aggregate content and explore other bio-based materials to further enhance the performance and sustainability of ecological concrete.

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The influence of sawdust on the microstructure, mechanical and durability performance of a cement-based mortar

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Keywords: sawdust, mortar, strength, microstructure, durability

Introductory remarks

The use of waste to replace part of the natural rocky aggregates or cement to reduce the environmental impact of cementitious materials is a main concern. Wastes with a mineral or an organic origin are often investigated. The latter may consist of sawdust, which added to the cementitious blends, may reduce the concrete weight, by maintaining an acceptable mechanical performance. On the other hand, the durability of cementitious mixes may be negatively affected by the sawdust addition, which require a higher amount of water to achieve an adequate workability. In the cement-based blends, the water content is kept constant and the sawdust dosage is set relatively low to keep the porosity under control. Additionally, the release of organic compounds, such as tannins from a sawdust composed of different wood species, is expected to influence the frost behaviour and the resistance to chloride penetration of the mortar blends.

Experimental procedure

A CEM II A/ LL 42.5 R (450 g), aggregates 0-4 mm (1350 g), water (225 g), superplasticizer (0 g, 2.25 g, 4.5 g) and sawdust (0 g, 9 g, 18 g) are mixed (EN 1015-2 standard). The sawdust is added to the blends and not used as a fine natural aggregate replacement. In fact, the influence of such particles on the durability is the main issue to clarify. The slump, density and porosity of the mixes with a dosage of 0% sawdust (mix SD0), 2% sawdust (mix SD2) and 4% sawdust (SD4) by volume of sawdust are measured in the fresh state (EN 206 standard). The compressive and flexural strength on 40 x 40 x160 mm prisms (EN 1015-2), the chloride penetration resistance on 50 mm diameter cylinders (SIA 262/1 appendix B) and the freeze / thaw resistance in the presence of deicing salts (SIA 262/1 appendix C) are tested.

Main results and discussion

The reference blend exhibits a 28 days compressive strength up to 58.5 ± 0.4 Mpa. The blend SD2 shows a value of 29.7 ± 0.7 MPa, while the mix SD4 reaches a value of 34.5 ± 1.7 MPa. The density lowers from 2380 kg/m^3 (SD0) to 2120 kg/m^3 (SD2) and 2180 kg/m^3 (SD4). The addition of sawdust decreases the compressive strength and the density, due to the intrinsic light and soft nature of the wood particles. The values can be maintained around 30 MPa and the workability is achieved by adding the superplasticizer. Similarly, the flexural strength ranges from 9.1 ± 0.4 MPa (SD0), to 5.5 ± 0.7 MPa (SD2) and 5.9 ± 0.3 MPa (SD4). The chloride penetration increases from 12.2 ± 1.1 x 10^{-12} m^2/s for the reference specimens (SD0) to 16.8 ± 1.3 x 10^{-12} m^2/s (SD2) up to 18.4 ± 0.8 x 10^{-12} m^2/s (SD4). The slightly higher penetration of chlorides within the sawdust -enriched sample is due to the higher porosity created around the wood fine particles. The superplasticizer-induced porosity, although not always interconnected, also contribute to the higher chloride penetration. In this concern, the release of tannins to act as a chloride binding compounds is not observed. The resistance to the surface scaling during the frost tests is increased, thus exhibiting values from 14'900 ± 2756 g/m^2 (SD0) down to 200 ± 64 g/m^2 (SD2) and 900 ± 874 g/m^2 (SD4). The higher porosity of the sawdust samples promotes the accommodation of the internal stresses that may arise during the frost action. Therefore, the surface scaling is reduced. An investigation of the

microstructure indicates an elongated platy, foil-like morphology with some fine porosity of the sawdust. The reference specimens (SD0) shows widespread cracking through the cementitious matrix and through the aggregates, while the specimens with the addition of sawdust exhibit a significantly reduced cracking pattern. The water addition of the reference specimens and the sawdust-enriched mixtures was kept constant to avoid a difference in the content of the pores. Nonetheless, the porosity is especially present around the sawdust particles, while the addition of the superplasticizer seems to further create a homogeneous distribution of round pores for the accommodation of the tension during the freezing action. The sawdust and the superplasticizer-induced porosity contribute to the higher frost resistance, while decrease the chloride and the mechanical resistance.

Conclusions

The sawdust-enriched specimens exhibit a lower compressive and flexural strength at 28 days. The durability with respect to the chloride penetration is negatively affected with sawdust, due to the presence of pores around and within the sawdust particles. Furthermore, the round pores induced by the superplasticizer, also exhibits a detrimental effect on the mechanical performance. The sawdust and the presence of tannins do not influence the chloride binding capability of the cementitious mixes. On the other hand, a relevant increase in the frost resistance is measured, due to the accommodation of the stresses with the artificially formed porosity within the specimens.

Feasibility of Cross-Laminated-Timber Production In The Netherlands

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Keywords: CLT, construction industry, environment, agroforestry, The Netherlands.

Cross-Laminated-Timber (CLT) is an environmentally friendly construction material which is suitable to replace concrete and steel in mid- and high-rise buildings. The global usage of CLT is expected to grow annually by 12.6% until 2027. Due to a housing shortage as well as the tightening environmental regulations an increased use of CLT seems likely in The Netherlands. Here we expect the number of wooden residential buildings to rise by around 20% every year until 2030. This could require an annual production of 250.000m^3 to 500.000m^3 of timber.

The advantages of CLT can be summed up as follows (Brandner, 2013; Pierobon et al., 2019; Quesada et al., 2018):

- Lightweight, the strength to weight ratio of wood product is high the crosswise configuration is amplifying this strength.
- Ability to be prefabricated, steps such as milling and sawing can already be done automatically in the factory as opposed to doing it by hand on the building site.
- Lower environmental impact, due to the relative low production emissions. If sequestered carbon starts playing a bigger role in regulations environmental benefits of CLT can be improved.
- Ability to carry loads out of plane, making CLT especially attractive to build floors with. In particular. floors of high-rise buildings.
- Good thermal insulation properties timber generally has quite good insulation properties (Sun, Li & He, 2020).

This paper came about by preliminary research followed by four semi structured interviews. The feasibility of a CLT supply chain in The Netherlands is explore by following these main research questions:

- Is it feasible to produce Cross Laminated Timber (CLT) in The Netherlands and what are the conditions to do so?
- Is it feasible to supply a CLT factory with Dutch production wood?

A Dutch high-rise building in The Netherlands called HAUT consists of 52 apartments and is built with 2.800 m^3 of timber. This results in a need of approximately 54 m^3 of wood per apartment (Wind, 2022). Another building has been built containing 23 apartments with 1.000 m^3 of wood resulting in 43,5 m^3 per apartment (Lend Lease, 2013). These apartments were not completely built in CLT but also with other timber products. It still gives a good proxy for the number of houses that can be built with production volumes of 20.000 m^3 to 100.000m^3 CLT per year. When these production quantities are divided by 50 m^3, which seems to be a good ballpark figure, it results in a total of 400 to 2.000 apartments annually. As discussed before a factory in the Dutch context is most likely to be able to produce nearly 2.000 apartments per year.

The approximately 950.000 m^3 of industrial roundwood being produced from Dutch forest has been relatively stable over the last ten years (Teeuwen, et al. 2020). The most popular lumber for the production of CLT is spruce, but other types like fir, douglas and larch are also used. (Centre for the promotion of Imports, 2017). A total of 690.000 m^3 of pine, douglas, spruce and larch wood were produced in the Netherlands in 2014. Of the most popular CLT wood, spruce only 76.000 m^3 was produced. On average, 46% of the wood is sawn/veneer wood and thus useable for CLT production (Probos, 2014). This results in a total of approximately 317.500 m^3 wood being available for the industrial production of CLT of which 35.000m^3 being spruce. A single large factory needs 120,000m^3. It is thus physically possible to supply a factory with Dutch grown wood, however one third is a significant portion of the total and the amount of spruce available is too limited. Therefor it is unlikely for a CLT factory to be fully supplied with Dutch grown wood which is suitable for CLT production.

We conclude that it is feasible to add The Netherlands to the list of CLT producing countries. Setting up a factory including land and the building can cost anywhere from 14 to 40 million euros. On an annual basis such factory can produce between 20.000m^3 and 100.000m^3 of CLT for 400 to 2.000 apartments. To guarantee international price competitiveness a production capacity of at least 50.000m^3 seems to be needed, while a larger highly automated facility of nearly 100.000m^3 would better suit the Dutch context. Because of the limited availability only a part of the required timber for a factory can realistically be of Dutch origin. Creating new Dutch production forests is not economically viable as the forest industry in the Netherlands is already barely profitable and the acquisition of land too expensive or time consuming. It could be beneficial to locate a factory in the vicinity of a Dutch production forest, however a logistically strategic position for importing timber seems more important.

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Thermal and mechanical performance of earth composites with rice husk shape-stabilized phase change material

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Keywords: Phase Change Material, Rice Husk, Earth Mortar, Thermal Behavior, Compressive Strength.

The building sector is one of the largest energy consumers worldwide, accounting for approximately 30% of global final energy use, with a significant portion attributed to heating, ventilation, and air conditioning (HVAC) systems. Reducing energy consumption in buildings is essential for mitigating environmental impacts and enhancing sustainability in the construction sector. This challenge is particularly relevant in regions with extreme climates, where maintaining indoor thermal comfort often requires intensive use of heating and cooling systems. Improving the thermal performance of buildings is a key strategy to minimize energy demand while ensuring occupant well-being. Among the various solutions investigated in the literature, Phase Change Materials (PCMs) have shown great potential for regulating indoor temperatures by storing and releasing latent heat, functioning as thermal energy storage systems.This study investigates the thermal behavior and compressive strength response of earth composites integrated with shape-stabilized PCM, with potential applications in façade elements. For this purpose, bio-based PCM with a melting point of 29°C was incorporated into rice husk (RH) to produce bio-aggregates using the shape-stabilized technique. The process was conducted in a controlled environment at 40°C and atmospheric pressure. The PCM content incorporated into the RH was 85% of its total PCM absorption capacity, minimizing losses during the RH-PCM production process. The physical properties of the bio-aggregates were evaluated, revealing lower water absorption of RH-PCM compared to pure RH, which highlights the pore filling of the RH-PCM and consequently, its higher density. Earth composites were produced with volumetric contents of 8% and 40% bio-aggregate (RH and RH-PCM, individually), with a reference mixture produced without bio-aggregate inclusion. The composite matrix consisted of earth, cement, lime, and sand, along with water and superplasticizer. For the compressive strength test, four cylindrical samples (50 mm in diameter and 100 mm in height) were tested after 28 days of curing using a Shimadzu 1000 kN press at a displacement rate of 0.3 mm/min. Compared to the reference mixture, a reduction in compressive strength was observed in mixtures containing bio-aggregates (particularly at higher contents), which can be attributed to the presence of RH. However, PCM incorporation did not result in a significant loss of mechanical performance of the RH-PCM mixtures, when compared to the ones with equivalent RH contents. Thermal behavior was evaluated by the German dynamic sphere calorimetry test, known as the DKK test (*dynamische Kugel-Kalorimetrie*). This test consists of monitoring the temperature evolution of spherical specimens over time as they are subjected to temperature variation. For this purpose, three spherical specimens with a diameter of 70 mm were tested, with thermocouples positioned at the center and on the surface of each sphere. The samples were exposed to a temperature variation from 10 ± 2°C to 55 ± 2°C for three hours during the heating phase, followed by the reverse process during the cooling stage. The results indicated that, although a slight deviation in the curve of the composite with 8% RH-PCM was observed at the PCM's melting point temperature, the influence on thermal behavior was negligible compared to the reference mixture. However, when the RH-PCM content was increased to 40%, a distinct shift to the right of the composite curve near the 29°C plateau was observed during the heating phase, highlighting the PCM's ability to store heat during its phase transition. These findings suggest that by applying an appropriate methodology for incorporating PCM into a porous medium, combined with proper mix design and material characterization, it is possible to develop earth composites with PCM that have the potential to enhance thermal comfort in buildings when used in façade elements.

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Upcycling Waste Wool for Regenerative Building Retrofits: A Biocomposite Approach

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Keywords: Waste Wool, Biocomposite, Retrofittable, Circular Design, Regenerative Design

As global temperatures continue to rise due to anthropogenic carbon emissions, the building sector remains a major contributor to the poly crisis as both a source of energy-related emissions and a primary driver of legacy extractive practices. While policies and certification programs have made strides in improving energy efficiency, reliance on carbon-intensive foam insulation and petroleum-derived synthetic building materials persists. This research presents a novel approach to decarbonizing the built environment by developing wool-biocomposite panels as exterior retrofit insulative cladding, leveraging waste wool as a sustainable alternative to conventional insulation materials.

This research introduces an upcycled wool bio-composite panel that capitalizes on the existing waste stream in wool production, where only a certain quality and grade of wool fibers enter the textile process chain. According to literature, at the production stage, only about 25% of the wool produced in Europe, and 5% in Italy in particular, is considered usable in the textile industry. In manufacturing, 10-15% of wool ends up as waste. In addition, the demand in the textile market is being overtaken by synthetic fibers, leading to an increase in surplus wool. While the potential of wool as an insulative material has been used for centuries and is well documented, scalability and durability concerns have hindered its widespread application. Building off the author's previous findings that indicate interior retrofitting of building insulations lacks reasonable CO2e and cost payback, this work introduces a novel biocomposite panel that aims to overcome these limitations by providing an exterior, retrofittable insulation panel that is a durable, structurally stable, and moisture-resistant alternative to traditional insulation.

The proposed retrofittable cladding system utilizes a novel "GHOO" (Grey Hydro Oxide Output) keratin-based biopolymer extracted from waste wool. This process involves alkaline treatment and mechanical energy to extract keratin-rich gel. The extracted keratin gel is then crosslinked with an organic acid and combined with residual wool fibers before being heat-pressed into rigid panels. This method eliminates petrochemical additives, resulting in a biocomposite with mechanical properties comparable to medium-density fiberboard. Further, depending on the composition of the GHOO polymer matrix, the residual wool fibers retain the natural ability to trap air through their kinks and bends, enhancing thermal performance, while the GHOO polymer matrix ensures mechanical stability and weather resistance.

This paper first introduces formulations and methods of making the novel wool bio-composite panels; it then demonstrates the mechanical performance of said panels and provides a full life cycle CO2e emissions evaluation of a potential retrofittable building product. Mechanical performance is demonstrated using ASTMD790 three-point bending testing. Results show that the wool biocomposite exhibits mechanical

strength equivalent to wood medium-density fiberboard. A full life cycle analysis is provided following International Organization for Standards and European Standards for product life cycle assessment. Comparisons between business-as-usual polyisocyanurate and wood fiberboard insulation are reported. Early results indicate that the wool panels provide functionally equivalent insulation at a comparable or reduced total life cycle carbon emissions relative to the polyisocyanurate board and wood fiberboard, at 9.1 and 9.68 (-7.66 w/ biogenic carbon) kg CO2e per 1 m2 at 20 mm thickness, respectively. These results are expanded in a discussion that evaluates the merits of transforming an underutilized agricultural byproduct into a high-performance and retrofittable building material, including the potential for biogenic carbon storage associated with intelligent regenerative sheep management in the Northeast United States.

The paper concludes that novel upcycled wool bio-composite panels offer a viable pathway for reducing reliance on petrochemical-based insulation using a durable, structurally stable, and moisture-resistant retrofittable insulation panel that offers a regenerative design solution across the entire lifecycle ecology of a prevalent waste stream, wool.

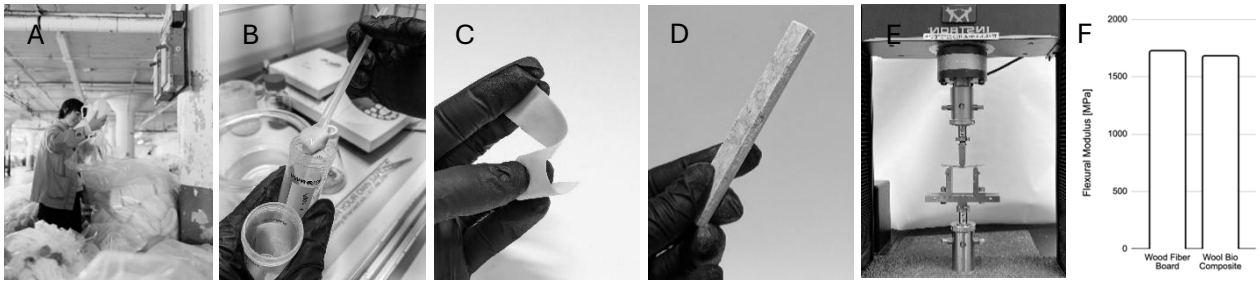

Figure 1 Sample of research of the waste-wool-based biocomposite: A) Sourcing of waste wool at American Woolen Company. B) Keratin gel extracted from waste wool. C) Cross-linked GHOO polymer film. D) GHOO wool-based biocomposite sample. E) Mechanical characterization testing. F) Early mechanical testing results for wood fiberboard (n=2) and wool bio-composites (n=1).

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Use of recycled fibre and processing waste fibre to bio-based composites via compression moulding

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Keywords: recycling, bio-based, compression moulding, circularity, wind turbine blade waste

Fibre-reinforced polymer composites are widely utilized in various high-performance applications requiring optimal strength-to-weight ratios. They are used in many fields, including automotive, aerospace and energy industries, for instance wind turbine blade (WTB), which features synthetic E-glass fibres (GFs) as reinforcement within a fossil-based thermoset polymer, which provides both performance and durability. However, the ageing of wind turbines in the energy sector is leading to the decommissioning of approximately 3800 blades per year in Europe, raising urgent concerns about their recyclability and material reuse. The complex structure and thermoset nature of conventional GF composites prevent effective treatment of end-of-life products, leading to a high carbon footprint, resource depletion, and limited recyclability. As a result, there is growing interest in developing more sustainable alternatives using bio-based resins and recycled glass fiber, in this case, WTB recycled fibers. Utilizing these recycled materials can significantly reduce landfill reliance and the environmental burden associated with virgin fiber production.

This research contributes to ongoing efforts in sustainable engineering by providing insight into how industrial waste and renewable resources can be transformed into viable structural materials, offering a practical path forward for green composite manufacturing. Through this integrated approach, the study seeks to demonstrate that environmentally conscious composite design can be achieved without compromising material functionality, paving the way for scalable, low-impact composite solutions across multiple industries.

One promising strategy to enhance the sustainability of composite materials is the incorporation of recycled fibres, particularly recycled glass fibres, into second-generation composites. Two primary sources of recycled GFs are currently being explored: (i) production waste from manufacturing processes of wind turbine blades, which typically consists of clean and continuous fibres with no degradation, and (ii) shredded material from end-of-life wind turbine blades, which is increasingly available due to decommissioning and blade replacement activities. While the second source of recycled material is abundant, the provided fibre presents challenges due to contamination, fiber damage, and the presence of residual matrix materials. In this study, both types of recycled GF—processing waste and shredded wind turbine blade material—are combined with a bio-based resin to develop new, more sustainable composite panels. By substituting virgin GF and fossil-based polymers with recycled reinforcements and renewable matrix materials, this approach seeks to support circular economy principles in composite manufacturing. A systematic evaluation of the compression moulding process is conducted, focusing on key parameters such as curing time, curing temperature, fibre-to-resin ratio, and pressure. These parameters are known to influence not only the mechanical performance and reliability of the composite but also its overall environmental impact through energy consumption during curing and material efficiency. The aim of this work is to produce high-performance, sustainable composites using recycled glass fibres and bio-based resin. Understanding how recycled fiber characteristics and processing conditions interact is essential for maximizing the performance of eco-friendly composites while minimizing their ecological footprint.

Valorisation of Biomass Fly Ash in Soil Stabilisation and Cement-Based Applications: Insights from Two Case Studies

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Keywords: Biomass fly ash, soil stabilisation, mechano-chemical activation, mineralogical analysis, cement-based application

Traditionally disposed of in landfilling, biomass fly ash (BFA) are increasingly subject to stricter environmental regulations. Rising disposal costs and the scarcity of suitable landfill space have intensified the need for alternative waste management strategies, which aligns with a growing demand in the construction and cement industry for secondary-sourced, low-carbon-emitting materials. BFA offer strong valorisation potential as a promising and readily accessible secondary resource. Their potential reactivity further strengthens their suitability for cost-effective, circular, and value-added applications. However, the practical implementation of such valorisation strategies poses significant challenges. BFA materials are characterised by inherent variability in composition, potential contamination, and specific storage requirements, all of which can affect their performance and safety in end-use applications. Furthermore, regulatory frameworks such as the Belgian "end-of-waste" system impose constraints by linking a specific waste material to a predefined valorisation route, potentially limiting innovation and reuse flexibility across sectors. Addressing these scientific, technical, and regulatory challenges is essential to unlocking the full potential of fly ash valorisation in sustainable construction and environmental applications.

This paper presents two successful case studies demonstrating the valorisation of BFA coming from two distinct industrial sources in different sustainable applications.
The first case involves the use of BFA as a substitute for lime in soil stabilisation. Experimental results conducted on low-bearing capacity silty soil demonstrate that at a comparable moisture content of 15%, incorporating 6 to 9% BFA significantly improves their geotechnical performance, increasing the immediate bearing index from 1% to over 15%, reaching comparable values to those obtained with 1,5% CaO addition. This enhancement successfully meets the requirement of the Qualiroutes technical specification for soil stabilisation without the need for additional lime. A characterisation study conducted on nine BFA samples over two years revealed notable variability in chemical and mineralogical composition, including lime content—which is essential for the targeted application. These findings highlight both the promising performance of BFA for soil stabilisation and the critical importance of managing material heterogeneity to ensure reliable and continuous reuse in geotechnical applications.

In the second case study, the potential use of biomass fly ash as a supplementary cementitious material (SCM) is explored. Two types of BFA, collected over six campaigns throughout one year from the same industrial site, underwent physical, chemical, and mineralogical analysis. The results revealed distinct differences in composition and reactivity, requiring specific pre-treatment strategies: either mechano-chemical activation or water-washing. Preliminary findings suggest that, when subjected to appropriate pre-

treatment, biomass fly ash can successfully replace conventional cementitious materials and reach similar compressive strength, while mitigating potential deleterious effect. Results revealed that mechanochemical activation allowed structural changes through high-energy grinding, aiming to reduce particle size and partially amorphise crystalline phases, increasing reactive silica content, thereby promoting reactivity. A 25% substitution of mechano-chemically activated BFA yielded a 7-day activity index of up to 98%, and 92% at 28-day. A parametric study confirmed the influence of grinding time and energy, revealing an optimal activation range. In parallel, 25% substitution of water-washed BFA showed an increase in 28-day activity index from 39% with 25% unwashed BFA substitution to 71%, highlighting the benefits of targeted treatment.

These two case studies demonstrate the technical feasibility and circular potential of biomass fly ash in both geotechnical and cementitious applications. They also emphasise the critical need for quality control, appropriate and tailored pre-treatment, and regulatory adaptability to enable the broader industrial adoption of BFA as a sustainable resource.

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Volume 1

Section 1.3: Geopolymers and Alkali-Activated Materials

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Application of MSWI Bottom Ash in Class F Fly Ash/Ladle Slag-Based Geopolymer: Pore Structure and Thermal Behaviour

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Keywords: Geopolymer; Pore structure; Thermal behaviour

In pursuit of sustainable construction materials, the reuse of municipal waste in geopolymer systems offers promising avenues for waste valorization and enhanced thermal resistance. This study investigates the application of Municipal Solid Waste Incineration (MSWI) bottom ash (BA) in conjunction with Class F fly ash (FA) and ladle slag (LS) to develop a ternary binder system capable of forming a high-temperature insulating coat on building structures. The core objective is to evaluate the feasibility of incorporating BA into a FA/LS geopolymer matrix to meet structural and thermal performance criteria. Through a comprehensive approach involving full-scale pore structure characterization and thermal behavior analysis, the study aims to reveal the influence of BA on the microstructure and performance of these geopolymers. Several binder combinations were prepared with varying proportions of FA, LS and BA, including ternary blends such as G8.15 (80 wt.% FA, 15 wt.% BA, 5 wt.% LS), binary system G8.00 and unary system G10. These samples underwent comprehensive pore structure characterization using three techniques: nitrogen adsorption/desorption (NAD) for analyzing gel and small capillaries, mercury intrusion porosimetry (MIP) for quantifying medium and large capillaries and micro-computed tomography (Micro-CT) for 3D visualization of internal macroporosity and macrostructure. The NAD results indicated a mesoporous (< 50 nm) volume of 0.07 – 0.09 cm^3/g across all samples. In the binary and ternary systems, gel pores contributed approximately 25% of the overall porosity, whereas in the fly ash-only system, over 80% of the porosity was due to small capillaries. Although the nanoscale distributions were similar among the samples, BA-foamed systems showed distinct differences in capillary network compared to reference groups. MIP analysis revealed that capillary structure is significantly influenced by the system composition, especially the proportion of BA. Micro-CT analysis validated that increasing the BA content not only increased the width of macropores (over 100 μm) but also led to a higher modal pore density, resulting in visually more porous specimens. Particularly for sample G8.15 provided visual confirmation of macropore distribution and overall structural integrity. The images supported the earlier analytical results, showing enhanced pore complexity and spatial distribution due to BA addition. In terms of thermogravimetric behavior, the study found that LS contributes to the formation of gel phases that improve volume stability at high temperatures. The addition of BA further enhanced this effect, suggesting a synergistic interaction in the ternary system. Moreover, thermal conductivity measurements revealed that, within a given system type, the solid-pore network physically dominates heat transfer characteristics. When samples shared similar densities, the thermal conductivity was more influenced by the nature of the solid phase rather than pore volume alone. This highlights the importance of solid matrix composition in determining thermal insulation efficiency.
Overall, the incorporation of MSWI bottom ash into FA/LS-based geopolymers appears to be a viable and sustainable strategy for producing thermally stable and insulating construction materials. The pore structure and thermal behavior analyses demonstrate that proper formulation, particularly in the ternary system, can optimize both physical integrity and energy efficiency. This research not only promotes the recycling of municipal waste but also contributes to the advancement of high-performance, environmentally friendly building technologies.

Behavior of geopolymer composites under thermal exposure: A combined experimental and modeling study

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Keywords: Alkali-activated material, Geopolymer, High temperature, In-situ, Modeling

Background

Building fire hazards have posed significant risks to human beings and property throughout history. Ordinary Portland Cement (OPC), as the most commonly used building material, the OPC-based concrete exhibits unsatisfactory high temperature performance, resulting in spalling, drastic strength loss, and melting with increased temperature up to 1000 ºC. It emphasizes the necessity of developing innovative fire/high temperature resistant materials for construction practices.

In recent decades, alkali-activated materials (AAM) have emerged as a sustainable solution for low-carbon emissions building and construction practices. By applying industrial by-products or wastes, for instance, fly ash, slags, municipal solid waste incineration bottom ash as precursor, a sodium or potassium alkali solution is used as activator. Among which, alkali-activated Class F fly ash, also termed as geopolymer, represents one of the most promising fire/thermal resistant materials due to its ceramic-like properties. Although geopolymer exhibits better properties than normal OPC-based concrete after high-temperature exposure, its in-situ thermal behavior remains unclear and requires further investigation to enable practical applications.

Methodology

This work aims to clarify the thermal behavior of geopolymer-based mortar through a combined experimental and numerical simulation approach. In this study, geopolymer mortar was prepared by using a composite binder with Class F fly ash (80 wt.%) and ladle furnace slag (20 wt.%). A mix of sodium hydroxide and sodium silicate was used as alkali-activator. The equivalent sodium percentage (Na_2O%) and silicate modulus (Ms) were kept constant at 6 and 1.5, respectively, and a water-to-binder mass ratio of 0.4 was applied. The distribution pattern of sand aggregates (below 4 mm) was designed according to the modified Andreasen and Andersen (A&A) model. Several in-situ thermal properties in aspects of thermal conductivity, linear deformation, and compressive strength were measured to evaluate the performance of geopolymer-based mortar during high temperature exposure. In addition, the measured parameters were employed as input for the numerical modeling using Comsol Multiphysics 5.6 software to understand the heat transfer and the thermal stress evolving with increasing temperature.

Main results

Table 1. The mechanical strength of geopolymer mortar at different temperatures.

In-situ compressive strength (MPa)			
20 °C	300 °C	500 °C	700 °C
15.54	12.79	18.21	10.91

The results reveal that the designed geopolymer mortar exhibits a promising volumetric stability with almost no linear change till 400 °C, following a 0.6% expansion at 550 °C. After that, a continuous linear shrinkage of 4% is observed from 550 to 800 °C, which is related to thermal shrinkage. The compressive strength at different temperatures is shown in Table 1. The mechanical strength remains relatively stable up to 300 °C, with a noticeable increase at 500 °C. However, a strength reduction is detected at 700 °C. The heat transfer and thermal stress within the matrix are simulated and presented in Fig. 1. Due to the high thermal conductivity, the temperature of the sand aggregate rises faster than geopolymer binder, creating an obvious thermal mismatch between aggregates and binder, especially at high temperatures. As for thermal stress, the geopolymer binder demonstrates stable and low thermal stress as the temperature increases, due to its porous microstructure and inherent thermal stability. In contrast, the sand aggregate experiences a sharp rise in thermal stress from room temperature to 700 °C. The geopolymer binder exhibits a stable and low thermal stress with increasing temperature, owing to its porous microstructure and thermal stability. The sand aggregate shows a drastic increase in thermal stress from room temperature to 700 °C. Notably, because of the thermal incompatibility between geopolymer and sand, a distinct localized stress concentration is noticed in the interfacial zone. The findings of this work provided a comprehensive picture of geopolymer-based material evolving along with temperature.

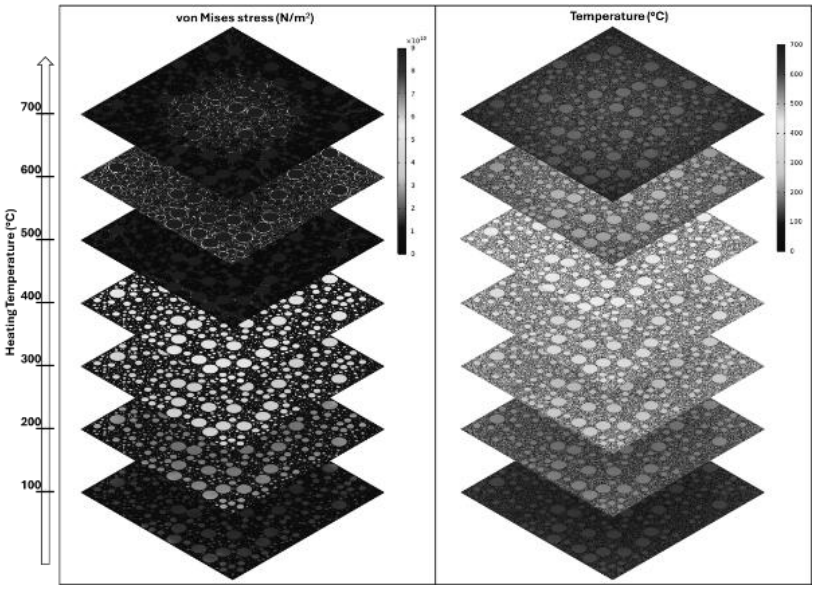

Fig. 1. The results of heat transfer modeling

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Behaviour of superplasticisers in alkaline solutions and their interactions with ground granulated blast-furnace slag and metakaolin particles: implications for low-carbon cements

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Keywords: Chemical admixtures. Low-carbon cements. Calcined clays. Net-zero future. PCE.

Supplementary cementitious materials (SCM) such as ground granulated blast furnace slag (GGBFS) and metakaolin are heavily used in modern cement formulations, including in Portland cement–SCM blends, alkali-activated cements (AAC), and limestone calcined clay cements (LC^3). These cements exhibit low associated CO_2 emissions compared to traditional Portland cement, helping reduce CO_2 emissions in the cement industry. Chemical admixtures, such as superplasticisers, are essential for large-scale applications because they enhance concrete fluidity without adding extra water, improving workability in the fresh state and reducing hardened concrete porosity, thereby enhancing mechanical performance and durability. While superplasticisers are crucial for modern concrete formulations based on Portland cement, they are often less effective in sustainable cements such as AAC, blended cements, LC^3, etc. This knowledge gap and scientific challenge motivated us to understand one of the mechanisms behind the diminished behaviour of superplasticisers in alkaline solution. This study examined the behaviour of lignosulfonate-, naphthalene sulphonate-, and polycarboxylate-based superplasticisers in AAM-relevant NaOH and Na_2SiO_3 solutions. Their interactions with ground granulated blast furnace slag (GGBFS) and metakaolin (MK) in NaOH solutions with SiO_2, NaCl, and $CaCl_2$ electrolytes were also analysed. Fourier Transform Infrared Spectroscopy (FTIR), Dynamic Light Scattering (DLS), and Transmission Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (TEM/EDX) assessed superplasticiser behaviour, while Total Organic Carbon (TOC) measured adsorption onto GGBFS or MK. Zeta potential (ZP) measurements evaluated electrokinetic potential in alkaline conditions. Findings indicate that high alkalinity alters the ionisation state of the polymers and modifies the zeta potential of GGBFS and MK particles to more neutral values, leading to reduced mobility and solubility issues, causing subsequent agglomeration. $CaCl_2$ electrolytes enhanced superplasticiser adsorption. Lignosulfonate-based superplasticisers showed greater stability. These results suggest that improving polymer stability and promoting surface interactions are key strategies for developing next-generation superplasticisers with enhanced performance in low-carbon cement systems.

Developing new low-carbon fire-resistance geopolymer mortar by using vehicle glass waste as fine aggregates, recycled tyre steel fibres (RTSF) as additives.

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Abstract

The cement industry is a major contributor to global carbon dioxide emissions, creating an urgent need for sustainable and low-carbon construction materials. This study proposes the development of a new low-carbon fire-resistant geopolymer mortar using locally sourced ground granulated blast furnace slag (GGBS) and metakaolin as binders. Vehicle glass waste (VGW) is utilized as fine aggregate, and recycled tyre steel fibres (RTSF) are incorporated as additives to enhance performance.

The integration of VGW not only diverts significant amounts of glass waste from landfills but also contributes to the fire resistance of the geopolymer mortar. However, the irregular shape, size, and thermal behavior of VGW can compromise the material's mechanical integrity under high temperatures. To mitigate these challenges, RTSF is used to enhance the toughness of the mortar. The inclusion of RTSF improves stress distribution and crack resistance, particularly under thermal stress, making the matrix more resilient during fire exposure.

This research investigates the combined effect of VGW and RTSF on the mechanical and fire-resistant properties of the geopolymer mortar. The study involves a comprehensive literature review, material characterization, and experimental evaluation to optimize the mortar mix design. By leveraging industrial waste materials, this work contributes to the development of a sustainable, low-carbon alternative to traditional cement-based mortars, aligning with global efforts to reduce environmental impact in the construction industry.

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Effect of calcium formate on strain-hardening CaO-activated GGBFS composites

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Keywords: Cementless, high-performance composites, CaO activation, Carbon footprint, Human toxicity

Cement production is known to emit a large amount of CO_2, contributing to around 8% of global emissions. To reduce this environmental burden, alkali-activated slag concrete (AASC) using industrial byproducts like ground granulated blast furnace slag (GGBFS) has been studied as a potential alternative. Although AASC shows good mechanical performance and durability, it still relies on high-alkaline activators such as sodium silicate solutions, which cause rapid setting, high pH, and safety issues. Recently, CaO-based activation has gained attention as a more practical and safer alternative. In particular, using calcium formate ($Ca(HCOO)_2$) as an accelerator has shown potential to improve early-age strength in CaO-activated GGBFS systems. However, research on applying this system to high-performance composites is still limited. Especially for high-performance concrete, it is essential to demonstrate not only high strength but also other properties such as high strain capacity. This study aims to develop a CaO-activated strain-hardening cementless composite (SH-CASC) with enhanced mechanical and environmental performance by incorporating calcium formate. Six different mixtures were designed with calcium formate ranging from 0% to 5% by binder weight. Polyethylene (PE) fibers were used to induce tensile strain-hardening behavior. The effect of calcium formate on hydration was investigated through isothermal calorimetry and thermogravimetric analysis (TGA), and pore structure was analyzed using mercury intrusion porosimetry (MIP). Flowability tests were also conducted to check workability. Compressive strength was tested and tensile behavior was evaluated using direct tensile tests. To understand fiber–matrix interaction, single fiber pullout tests were performed. Additionally, life cycle assessment (LCA) was performed to compare the environmental impact, particularly CO_2 emissions and toxicity, with conventional cement-based and alkali-activated composites. The results showed that calcium formate accelerated hydration and improved early compressive strength. The mixture containing 3–4% calcium formate showed the most balanced performance, with improved pore structure and stronger fiber–matrix bond, which led to increased tensile strength, strain capacity, and energy absorption. Pullout test results supported this, showing higher frictional resistance. The developed SH-CASC achieved strain-hardening behavior comparable to cement-based SHCC without using Portland cement or liquid alkalis. In terms of sustainability, the SH-CASC showed significantly lower CO_2 emissions and health-related impacts. Based on these results, calcium formate is considered effective in improving the performance of CaO-activated SH-CASC without compromising environmental benefits. This study suggests that SH-CASC with calcium formate could be a strong candidate for sustainable, high-performance cementless construction materials.

Effect of Calcium Hydroxide on Biomass Wood Ash-Based Alkali-Activated Mortar

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Keywords: Waste valorization; mechanical properties; mechanism; lifecycle assessment; eco-binder.

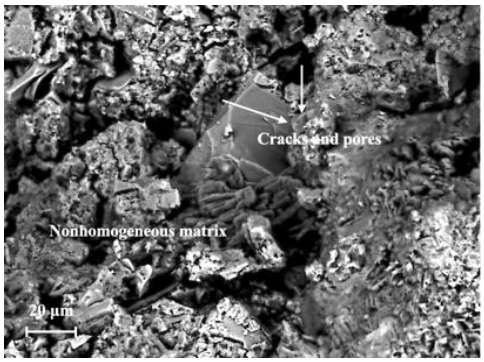
With the worldwide promotion of renewable clean energy, biofuel energy based on the combustion of wood sawdust and chips has witnessed significant growth in recent years, especially in countries with abundant forestry resources. This brings forth the challenges of waste management of biomass wood ashes (BWAs), which are a by-product of wood burning. Except for a small quantity of them consumed in the manufacture of agricultural fertilizers, most of them are disposed of in landfills, arousing a great concern for the environment. One more sustainable possibility is the valorization of these ashes as raw materials to produce building and construction materials. There is already some research regarding the BWA utilization in cement-based materials as a partial replacement for Portland cement or aggregates. Also, some investigations focused on its application in alkali-activated materials as a binary or ternary precursor. These studies primarily utilized BWA at a small ratio due to the consideration of mechanical property evolution; however, regarding the possibility of developing alkali-activated materials based on 100% BWA, the investigations are still limited.

Under this background, an alkali-activated mortar (AAM) was developed, using two categories of BWAs (biomass wood fly ash and biomass wood bottom ash) as precursors. Recycled sand from biofuel plants replaced natural river sand due to the consideration to conserve non-renewable natural resources. Besides sodium hydroxide (SH) and sodium silicate (SS), in order to improve the eco-efficiency, a more sustainable activator, calcium hydroxide (CH), was added as a ternary activator at the ratio of 0, 5, 10, 15, and 20% by precursor weight. Its effects on AAM were assessed via mechanical strength, water absorption, and microstructural analysis which was conducted through SEM-EDS, XRF, XRD, and FTIR to also reveal the reaction mechanisms. The carbon footprint and energy consumption of the mortar production were evaluated via a lifecycle assessment.

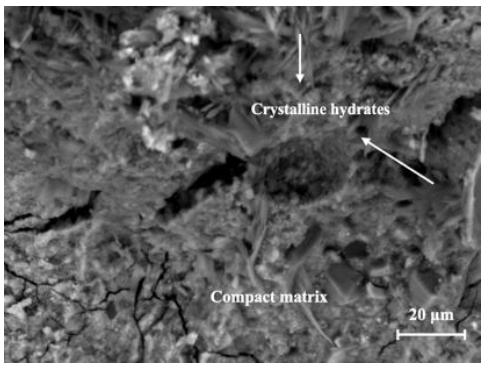
According to the obtained results, CH, as a ternary activator, served as an active source of calcium and can improve the alkalinity of the ambient. This importantly contributed to the enhancement of strength in a range between 16.64% and 24.26%. Its incorporation enhanced the densification of the AAM microstructure and was related to a reduction of water absorption. This was confirmed by the SEM graphs in Fig.1, the reference sample with 0% CH exhibited a mal-bond microstructure. With a 10% CH addition, a denser morphology was observed, with a decreased amount of micropores and gaps. The following increment of CH content to 20%, however, led to less densification of the microstructure and the propagation of voids. This corresponded well with the strength evolution. The shifts of bands aligning with the Si-O-Si, O-H, and C-O vibrations, compared to the raw materials, were observed in the FTIR spectra in mortar samples, indicating the formation of hydrates and carbonates. This was testified to in the XRD analysis, where crystalline hydrates were identified, together with an amorphous hydrate region. The intensity of the peaks belonging to calcium silicate hydrates showed an enhancement after adding CH, revealing its positive effects on the facilitation of the activation process. In the XRF analysis, the introduction of CH increased the Ca/Si ratio of the samples, which significantly influenced the mechanical properties of the mortar. In the lifecycle assessment, it is noted that BWA had very few greenhouse gas emissions and energy consumption, while most of the environmental impacts came from

alkali activators, especially SH and SS, which accounted for nearly half of the impacts. In contrast with them, CH contributed to much less impacts, with an energy demand of five times less than that of SH.

In conclusion, the valorization of biofuel energy wastes to be applied as precursors for alkali-activated materials greatly improved sustainability from the perspective of both waste management and building material production. The usage of CH as a ternary activator was sustainable and improved the mechanical properties of AAM due to its positive effects on facilitating the production of hydrates, improving the microstructure, and contributing to a more homogeneous pore structure.



(a) With 0% CH



(b) With 10% CH

(c) With 20% CH

Fig. 1 Micrographs of AAM samples

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Effect of fusion conditions on valorized waste-glass solution and its influence on the mechanical strength of binary blended geopolymer mortar

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Keywords: Geopolymer mortar, waste glass, sodium silicate, fusion conditions, mechanical strength

Sodium silicate is a primary activator in geopolymer production and is conventionally produced through energy-intensive processes involving quartz (SiO_2) and sodium carbonate (Na_2CO_3) at a temperature of 1200 – 1500°C. However, there is a need for eco-friendly approaches for synthesizing sodium silicate, especially from waste materials, to reduce resource depletion and energy consumption and promote industrial symbiosis and circular economy practices. Waste-based sodium silicates provide a sustainable alternative to conventional sodium silicate solutions and are vital in closing material loops in geopolymer production. Waste glass is an abundant industrial and construction waste that primarily composes silica (SiO_2), making it an effective silica source for synthesizing sodium silicate through alkali fusion. Despite potential benefits, the influence of fusion conditions (temperature and reaction time) on waste glass-derived sodium silicate composition, phase structure and reactivity remain underexplored. Therefore, this study investigated the effects of varying fusion conditions on the composition, phase structure and reactivity of sodium silicates synthesized from waste glass and their subsequent role in the strength development of geopolymer mortars. The findings contribute to optimizing the fusion process for improved material performance and sustainability in geopolymer applications.

This alkali fusion process involves thermochemical reactions between waste glass powder and sodium hydroxide (NaOH) at elevated temperatures, resulting in a reactive silicate phase suitable for geopolymerization. The fusion process was conducted at six different conditions: 500°C for 3 hours, 550°C for 2 hours, 550°C for 3 hours, 600°C for 2 hours, 600°C for 3 hours and 650°C for 2 hours. Afterwards, the synthesized powder sodium silicates were characterized using X-ray fluorescence (XRF) and X-ray diffraction (XRD) to determine their chemical composition and phase structure and assess how fusion parameters influenced their crystallinity and reactivity. Following characterization, the synthesized sodium silicates were dissolved in water to yield sodium silicate solutions (37.1% solids (Na_2O + SiO_2) and 62.9% H_2O) to match the composition of a reference commercial sodium silicate solution (10.6% Na_2O, 26.5% SiO_2, 62.9% H_2O). The resulting solution was combined with a 12 M concentration NaOH solution as a co-activator to prepare geopolymer mortars incorporating fly ash and ground granulated blast furnace (GGBFS) via two-part mixing. The mortar mix design comprised two mixes: Mix 1 (fly ash-to-GGBFS ratio of 7:1) and Mix 2 (fly ash-to-GGBFS ratio of 3:1), with alkaline-to-binder (AL/B) of 0.5 and sodium silicate-to-sodium hydroxide ratio (SS/SH) of 1.5. The mortar specimens were first cured thermally at 80°C for 24 hours and later cured ambiently (23 ± 2°C) for 28 days. The mechanical properties of the geopolymer mortars were evaluated through compressive and flexural strength tests at 7 and 28 days as per SANS 50196-1 to determine how the different fusion conditions affected strength development.

The results demonstrated that fusion temperature and reaction time were vital in defining the phase structure and reactivity of the sodium silicate, which directly impacted its ability to activate

geopolymerization. Lower fusion temperatures, notably 500°C for 3 hours, primarily yielded amorphous sodium silicate phases that were more reactive and led to improved strength development in geopolymer mortars. In contrast, higher temperatures, like 650°C, increased crystallinity, which decreased solubility and reactivity and reduced the mechanical performance of the mortars produced. The optimal mechanical performance at 7 days was obtained at 500°C for 3 hours, achieving compressive and flexural strengths of 32.60 MPa and 6.89 MPa for Mix 1 and 29.85 MPa and 3.25 MPa for Mix 2, respectively. However, when compared to the geopolymer mortars produced with the commercial sodium silicate, which achieved compressive strengths of 47.15 MPa and 46.09 MPa and flexural strengths of 5.87 MPa and 4.16 MPa for Mix 1 and Mix 2, respectively, the waste-glass-derived sodium silicate exhibited lower compressive performance despite comparable or even improved flexural strength. Hence, the results emphasize that controlling fusion conditions is essential for maximizing the efficiency of sodium silicate derived from waste glass as an alkali activator, thereby improving the performance of geopolymer mortars.

The implications of the findings of this study extend beyond strength optimization. Using waste glass for sodium silicate aligns with global sustainability efforts by diverting non-biodegradable waste from landfills and reducing the reliance on virgin raw materials. A low-energy alternative to conventional sodium silicate production is also provided, as the successful synthesis of sodium silicate using relatively moderate fusion conditions suggests that industrial-scale implementation could offer more cost-effectiveness in geopolymer technology. Given that the carbon footprint of geopolymer binders is already substantially lower than that of ordinary Portland cement (OPC), further improvements in the glass powder-based activator synthesis can improve its activation efficiency and contribute to making geopolymer materials even more viable and sustainable.

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Effect of superplasticizers on the pore system of hybrid fly ash and ladle slag based geopolymer

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Keywords: Geopolymer, Ladle slag, Superplasticizer, Pore structure

Introduction

Superplasticizers (SPs) are widely used to improve the fluidity of ordinary Portland cement (OPC) systems. Currently, commonly used SPs include naphthalene-based and melamine-based types (second-generation), as well as polycarboxylate-based types (third-generation). Owing to their superior performance in OPC systems, these admixtures have also been introduced into alkali-activated materials (AAMs). While most studies concentrate on the molecular design of SPs and their mechanisms of action or failure in AAMs, relatively few studies explore their influence on pore structure in AAMs. Therefore, the main objective of this study is to investigate the effects of two different superplasticizers on the pore characteristics of a geopolymer system.

Methodology

Class F fly ash (FA) and ladle slag (LS) were used as raw materials in this work. The mass ratio of LS to FA was fixed at 15/85 and the water-to-binder ratio was set as 0.4 for all samples. The alkali activator was prepared by mixing sodium hydroxide pellets with sodium silicate solution (Ms = 1.5, Na2O% = 6 wt%) and naturally cooled to ambient temperature for 24h before mixing. Two types of commercial SPs including polycarboxylate ether (PCE) and melamine/naphthalene sulphate (MNS) were introduced at dosages of 0.5%, 1.5%, 2.5% by the weight of the total binder. All samples were firstly cured at ambient temperature in the sealed molds for 24 h and then followed by another 24 h curing at 60℃. Before the BET and MIP test, the hardened samples at 28d were crushed into powders and particles and then immersed in isopropanol for 3 days and subsequently dried at 40℃ for 24h.

Results and discussion

The incorporation of SPs undoubtedly influences the pore volume and fraction. Generally, the pores are classified as gel pores (≤10nm), transitional pores (10-100nm), capillary pores (100-1000nm) and macropores (> 1000nm). According to the BET results, the addition of MNS reduces the content of gel pores and transitional pores as the MNS dosage increases, accompanied by a decrease in cumulative pore volume. However, the sample mixed with PCE exhibit the opposite trend for both gel pore volume and total pore volume. Notably, compared to the reference group, all dosages of PCE and only low dosage of MNS improve the gel pore volume which illustrates that the reaction process is promoted. MIP tests can measure a wider pore range from 6nm to 100μm. The results show that the porosity of all samples containing SPs remains nearly constant at approximately 38%, slightly higher than that of reference group. In addition, the increased MNS results in a higher median pore size. The pore diameter of the sample with 2.5% MNS reaches 84.2 nm, which is 18% higher than that of the reference group. Conversely, all samples with PCE show smaller median pore size from 65nm to 69nm. Moreover, the trend of the transitional pore volume fraction in the MIP test is comparable to that from the BET results. Specifically, the capillary pore volume fraction of samples with MNS increases as the MNS dosage rises, surpassing that of the reference group, which exceeds that of the samples with PCE. This could be attributed to two factors. Firstly, the workability of samples with MNS is lower, leading to a high capillary pore volume fraction. Secondly, the addition of MNS introduces more air bubbles into the geopolymer system, resulting in the formation of large capillary pores.

Conclusion

The addition of SPs modifies pore structure. PCE promotes the reaction process, thus improving gel pore formation and reducing median pore size, while MNS increases the volume of capillary pores due to a lower

workability and air-entraining effects, though overall porosity remains relatively stable.

Effect of waste from CETRIS boards production on the properties of alkali-activated materials.

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Keywords: Sustainability, CETRIS Boards, Waste Material, Alkali-Activated Material

Because of high carbon dioxide emissions in the world, to which cement production also contributes (around 7-9%), there has been a tendency to use alternative materials to Portland cement. Alkali-activated materials (AAM) have shown great promise in this area. The preparation of AAM usually involves the use of secondary raw materials, most often granulated blast furnace slag (GBFS). This, in combination with suitable activators, exhibits latent hydraulic properties. The use of waste material in alkali-activated material also has the potential to reduce the amount of landfill waste. During the production of cementitious particleboard (CETRIS), two types of waste are generated, either fine powder during the grinding of the final surface of the boards, or cuttings that are generated during the cutting of the boards to customer-specified dimensions. The waste from the production of CETRIS boards consists of fine wood chips and cement matrix. For alkali-activated materials, this waste material could potentially have a beneficial effect on extending the solidification time (due to possible leaching of the cellulose) and also increasing the strengths in the case of unhydrated cement particles that may be contained in this waste. Grinding waste (waste 1) was used for the research; it consists of chips of different sizes and shapes, which are coated with the original cement matrix; individual grains of hydrated cement are present only in a lower proportion (Figure 1a). The waste in the form of cuttings has been further treated by various crushing methods. Some of the waste was crushed with a jaw crusher (waste 2), but this treatment was very dusty and not very effective. The resulting waste material contained chips of larger sizes, usually elongated in shape, the grains of hydrated cement themselves being almost undetectable (Figure 1b). For the second variant of crushing, a shear mill crusher (waste 3) was used, which produced finely ground waste of the most homogeneous fraction (0/4) and visibly contained chips of almost identical sizes (Figure 1c).

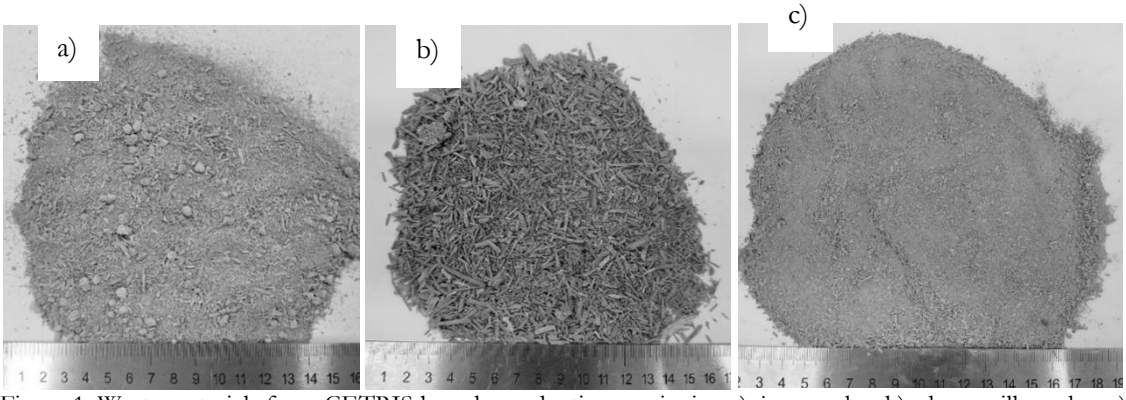

Figure 1: Waste materials from CETRIS boards production – gringing a), jaw crusher b), shear mill crusher c)

In the first phase of the research, 3 types of leachates were prepared from the above-mentioned waste materials. The leachates differed in the length of leaching and also in the ratio of waste material to demineralised water. The first set of leachates (AAM1) was prepared for 72 hours with low mixing intensity, the ratio of waste to demineralized water was 1:6. The second set of leachates (AAM2) was prepared for 3 hours with high mixing intensity, the ratio of waste to demineralised water was 1:2. The third set of leachates (AAM3) was prepared for 3 hours with high mixing intensity and then with low mixing intensity for 69 hours, the ratio of waste to demineralized water was 1:2. There was also an attempt to form leachates of waste materials in a solution of alkaline activators (sodium water glass and solution of potassium hydroxide). These leachates could not be used because of their solidification, probably due to the presence of unhydrated cement particles. The effect of the leachates on the setting time of GBFS was tested using the Vicat instrument according to EN 196-3. A mixture containing 500 g of GBFS, 62.2 g of sodium water glass with 2.0 silicate modulus, 46.7 g of 50 % solution of potassium hydroxide and 90 g of water or formed leachate was designed for testing. The effect of all the prepared leachates on the extension of the solidification time was low, almost insignificant. The results are shown proportionally in Figure 2.

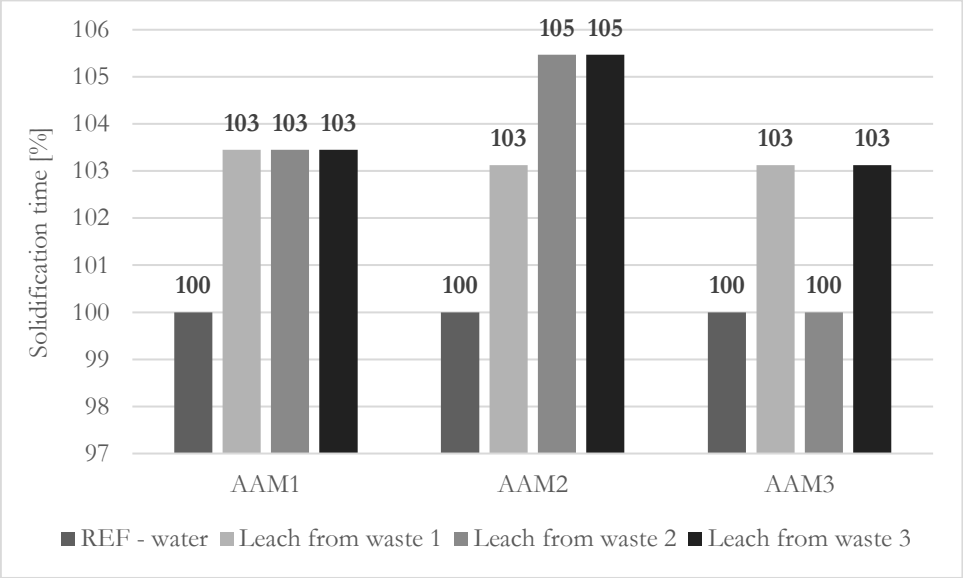

Figure 2: Bar chart of solidification time of different AAM mixtures.

Alkali-activated mortars have also been designed. Dried waste materials were used in the mortar mixes as a partial replacement (10, 20 and 30%) of natural silica sands. Due to the high water absorption of the waste (about 45%), water was added to the mixes to soak it up. The samples were tested for bending strength and compressive strength according to EN 196-1. A decreasing trend in the values of volume density, bending strength and compressive strength with increasing replacement of natural aggregate was observed for the samples.

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Effects of Calcium/Aluminum Supplementation on the Properties of Alkali-Activated Low-Reactivity Simulated Lunar Soil

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Keywords: Geopolymer; Lunar soil; Calcium/Aluminum Supplementation

Lunar exploration activities hold groundbreaking significance for advancements in multiple fields, with lunar construction being the primary objective of lunar exploration programs. Constrained by Earth-Moon transportation technology and costs, utilizing in-situ resources (such as lunar regolith and rocks) for construction materials proves more feasible and sustainable.While high-temperature sintering or melting enables 100% in-situ resource utilization, it demands extremely high energy, imposes stringent equipment requirements, and relies on molding templates, making it difficult to produce multi-shaped components for complex applications. In contrast, room-temperature forming—though requiring additional binders or specific materials (e.g., water, alkali activators, aluminosilicate mineral additives)—eliminates the need for complex material processing equipment. Combined with 3D printing technology, it enables mold-free, automated construction, offering significant advantages for complex architectural structures.Among room-temperature methods, alkali-activated geopolymerization for lunar regolith concrete is a promising approach. Water does not chemically participate in the reaction but serves as a reaction medium in the alkali-activation system, allowing its recycling. Activation efficiency depends on the amorphous reactive content and mineral composition of the precursor material. Existing simulated lunar regoliths (e.g., TJ-1, JLU-H, JSC-1A, JSC-2A, BH-1) exhibit higher reactivity than actual lunar regolith.This study employs WHU-L-1 simulated regolith, which closely matches actual lunar regolith in chemical and mineral composition, featuring high crystallinity and low reactivity. It was activated using low-alkali waterglass (4% Na_2O). ICP results confirmed WHU-L-1 released sufficient silicon but limited calcium and aluminum (XRD showed alkali activators primarily dissolved albite, pyroxene, and minor anorthite).Targeted supplementation with 10% or 20% calcium/aluminum sources (GGBS, MK, $Ca(OH)_2$, Al_2O_3) revealed calcium's decisive role in enhancing performance: GGBS and $Ca(OH)_2$ increased strength to 40.3 MPa and 9.98 MPa, respectively, versus 1.65 MPa (MK) and 0.59 MPa (Al_2O_3). Calcium sources accelerated heat release and shifted exothermic peaks earlier. Thermal analysis and FTIR confirmed calcium promoted more C-(A)-S-H gel formation. Unlike GGBS (generating C-A-S-H), $Ca(OH)_2$ produced C-S-H. Excessive $Ca(OH)_2$ failed to further boost strength (due to complete silicon consumption), whereas slag supplementation showed superior effects. SEM revealed denser microstructures with uniform gel distribution in calcium groups, versus porous, crack-prone structures in aluminum groups.This preliminary study will next investigate early-stage hydration under vacuum curing at varying temperatures, examining moisture loss and product formation, while integrating 3D printing to assess lunar construction feasibility.

Environmental sustainability and cost analysis of fly ash-based geopolymer mortars with varying compressive strength

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Keywords: Cost analysis, Geopolymer composite, Heat curing effect, Life cycle assessment.

The urgent need to mitigate the environmental impact of the construction industry, a significant contributor to global carbon emissions and resource depletion, has spurred extensive research into sustainable alternatives to conventional cementitious materials like Ordinary Portland Cement (OPC). In this context, fly ash-based geopolymer technology has emerged as a promising avenue, offering the dual benefits of valorizing industrial waste and significantly reducing the carbon footprint associated with binder production. This study delves into the state-of-the-art of fly ash-based geopolymer mortars, specifically examining their environmental sustainability and cost-effectiveness across a range of achievable compressive strengths, thereby addressing a critical aspect in the transition towards a more environmentally conscious and economically viable construction sector.

This study investigates the environmental and economic viability of geopolymer mortars produced using fly ash, alkaline activators (sodium silicate and sodium hydroxide), natural sand, and superplasticizer. By employing a factorial experimental design with varying alkaline activator-to-precursor ratios (0.6, 0.5), sodium silicate-to-sodium hydroxide ratios (2, 1.5, 1), and curing temperatures (50°C, 60°C) to achieve a target compressive strength exceeding 20 MPa, the research highlights the inherent environmental benefits and energy efficiency of geopolymer composites as alternatives to conventional cementitious materials. In total, four different geopolymer mortar were produced and two different heat curing regimes were applied on these mixtures. This study adhered to established testing standards for characterizing the fresh and hardened state properties of the developed geopolymer mortars. Specifically, the spread diameter of each mixture, a measure of flowability, was determined following the guidelines outlined in ASTM C1437-20. Furthermore, the compressive strength, a critical indicator of the hardened material's mechanical performance, was evaluated in accordance with the specifications of ASTM C109. These standardized testing procedures ensure the reliability and comparability of the obtained results within the broader scientific literature.

Beyond their reduced carbon footprint and reliance on industrial byproducts, a comprehensive cost analysis of these optimized geopolymer mixtures was conducted to assess their economic competitiveness. Furthermore, a detailed life cycle assessment (LCA) was performed to quantify the environmental impacts across the entire material lifecycle, from raw material extraction to production. This study contributes to the literature by providing a systematic evaluation of the interplay between processing parameters, cost, and environmental performance of geopolymer mortars. The integrated LCA and cost analysis, particularly for optimized mixtures achieving specific strength targets, offers novel insights for the broader adoption of sustainable construction materials. The compressive strength of geopolymer composites is significantly influenced by processing parameters. Notably, elevating the curing temperature proves to be a highly effective strategy for enhancing strength development. While reducing the sodium silicate-to-sodium hydroxide (Na_2SiO_3/NaOH) ratio can initially improve compressive strength, exceeding an optimal value leads to a subsequent decline. Conversely, a slight increase in compressive strength can be achieved by decreasing the alkaline activator-to-precursor ratio. Importantly, even at lower Na_2SiO_3/NaOH ratios, increasing the curing temperature remains a potent method for further strength enhancement. These interconnected effects highlight the complex interplay between mix design and curing regimes in tailoring the mechanical performance of geopolymer composites.

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Evaluating Admixture Effects on Rheology and Strength in Alkali-Activated Cement Systems

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Keywords: Alkali-activated cement, Admixture, Concrete, Mortar

The use of admixtures in Portland cement concrete and mortar is essential for improving the performance and properties of these materials. These additives, including plasticizers, superplasticizers, retarders, accelerators, and other chemical compounds, help optimize workability, durability, strength, and curing time. By improving the mix's efficiency, these admixtures contribute to resource optimization and adapt the material to specific environmental or operational conditions. However, when transitioning from traditional Portland cement to alkali-activated cement (AAC), it is essential to note that many additives commonly used in Portland cement may not be as effective or even compatible with AACs. This is due to the fundamental differences between these two types of cement, especially in their chemical compositions and setting processes.

Alkali-activated cements are characterized by a lower calcium content compared to Portland cement and undergo a different activation process, usually involving a combination of alkaline solutions and materials such as fly ash, slag, or metakaolin. This unique chemistry leads to a highly alkaline environment, which can interact in unpredictable ways with certain additives. For instance, plasticizers and superplasticizers that work well in Portland cement mixtures may not have the same effect in AACs or may even alter the hydration process, reducing workability or other undesirable outcomes. Therefore, the interaction between admixtures and the highly alkaline environment of AACs requires the development of specialized additives specifically designed for these materials.

Research on additives for AACs is still in its early stages, but the availability of such products is gradually increasing. New formulations are being developed to address the specific challenges posed by the chemistry of AACs, aiming to improve workability, enhance strength, and ensure long-term durability. As the construction industry increasingly turns to more sustainable alternatives like AACs, the demand for these specialized additives continues to grow. To optimize the performance of AACs, it is essential to design additives that can interact favorably with their unique properties.

This study investigated the influence of 33 different admixture combinations on the rheology and workability of a one-part AAC system based on slag as a precursor and a silicate activator. The admixtures included both organic and inorganic compounds. The objective was to assess the influence of these additives on fluidity, measured using the Kantro Cone test, and on rheological properties, evaluated with a parallel plates rheometer. The results revealed distinct behaviors when the additives were applied in different cement mixtures, such as paste, mortar, and concrete. Notably, 61% of the combinations reduced workability, 16% maintained it, and 26% improved it, with the latter combinations being selected for further testing in concrete and mortar.

When these selected combinations of additives were tested in concrete, they increased the slump measurement between 20% and 57%, indicating an improvement in workability. However, this was accompanied by a reduction in early-stage compressive strength, a critical factor for structural integrity. In mortar, using these admixtures resulted in a significant increase in fluidity, with the diameter expanding from 0 to 274 mm. However, similar to the concrete tests, there was a 35% reduction in early-stage compressive strength, indicating that while the admixtures improved workability, they also negatively affected the material's initial strength development.

In conclusion, while admixtures offer significant benefits in terms of workability and performance in both concrete and mortar, their impact on the early-stage strength of AACs needs to be carefully evaluated. The development of specialized additives for AACs is essential to ensure that these materials can achieve optimal performance in the

construction industry, balancing workability improvements with the necessary strength requirements for structural applications.

Evaluating the Potential of Waste Clay Sludge for Sustainable LC3 Cement Production

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Keywords: LC3; Calcined clay; Compressive strength, Sustainable construction, Waste management

The integration of waste materials into construction and building material production presents a significant potential contribution to the pursuit of sustainable development. This study evaluates the potential utilization of waste clay sludge (CSW), generated during the production of sanitary ware, as a calcined clay alternative in the production of limestone calcined clay cement (LC3). LC3 cement, a blend of calcined clay, limestone, clinker, and gypsum, is a promising alternative to OPC, offering up to a 40% decrease in CO_2 emissions while maintaining similar performance characteristics. Waste clay sludge contains significant amounts of clay minerals, making it a resource worth utilizing. Although the pozzolanic activity of raw clay materials is limited, the calcination process can enhance this activity. The chemical composition and mineralogical analysis of CSW were determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD). The waste clays were calcined at a temperature of 750°C to exhibit pozzolanic properties. The chemical compositions of mixtures in the literature studies were analyzed, and the limit values determined in the analysis results were taken into account in deciding the mixture ratios of LC3 cements to be prepared with waste clay. Following the analytical study, three LC3 cements were prepared with different replacement rates: LC3 (70-20-10), LC3 (60-30-10), LC3 (55-30-15). The flowabilities of the mortars and their compressive strengths following 3, 7, and 28 days of curing were determined. In addition, the strengths of mortars prepared with LC3 cements were compared with the strengths of reference mortars prepared with ordinary Portland cement. Results indicated that increasing clay content in LC3 cements reduced mortar flowability. Higher cement content generally led to higher long-term strength. The mortar incorporating waste clay sludge achieved 28-day mechanical performance comparable to the reference mortar. Reusing waste clay slurries within the construction sector may contribute to the minimization of sedimentation in the storage areas of the sanitary ware production industry, the conservation of non-renewable natural resources utilized in cement manufacturing, and the reduction of energy costs and CO_2 emissions associated with Portland cement production.

Evaluation of Alkali-Activated Limestone Calcined Clay Mortars for 3D Concrete Printing Applications

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Keywords: Limestone calcined clay, Lime, Rheology, Alkali activation, 3D concrete printing.

Limestone calcined clay (LC2) has gained significant attention as a supplementary cementitious material (SCM) due to its ability to reduce energy consumption and mitigate the carbon footprint associated with ordinary Portland cement (OPC). The combination of limestone and calcined clay enables the partial replacement of OPC while maintaining strength and durability. However, its use as an SCM is typically limited to a maximum 50% reduction in OPC utilization. This limitation restricts the full potential of LC2 in sustainable construction. To overcome this constraint, alkali activation offers a promising alternative by enhancing the binding properties of LC2, allowing it to function as a standalone binder rather than just an SCM. Alkali-activated materials (AAMs) have shown superior mechanical properties, durability, and sustainability compared to traditional cementitious binders. Additionally, their potential application in 3D concrete printing (3DCP) is of particular interest, as 3DCP is revolutionizing the construction industry by reducing construction time, labour costs, and material wastage. However, for effective integration into 3DCP, binders must exhibit tailored rheological properties, including controlled flowability, buildability, and setting time. The development of sustainable and cost-effective materials for 3DCP applications is, therefore, an urgent need.

This study aims to develop and optimize alkali-activated LC2 mortars for 3DCP applications. Various binder formulations were designed by modifying the alkalinity of the system using different dosages of sodium hydroxide, sodium silicate, and hydraulic lime. The selection of these alkaline activators was based on their ability to enhance the dissolution of aluminosilicates present in calcined clay, leading to the formation of a geopolymer-like binding matrix. The impact of different activator concentrations on setting time, workability, and printability was systematically evaluated. The study involved multiple experimental investigations to assess the suitability of alkali-activated LC2 binders for 3DCP. Flowability tests were conducted to determine the ease of material extrusion and its ability to retain shape upon deposition. Additionally, rheological tests were performed to measure yield stress, viscosity, and thixotropic behaviour, which are crucial parameters for ensuring the structural integrity of 3D-printed layers. Mechanical properties, including compressive and flexural strength, were also evaluated to confirm the material's performance. To validate the practical feasibility of the developed formulations, printing trials were carried out using a 3D concrete printer. The printability of different mixtures was assessed based on their deformation resistance and extrusion consistency. The most promising formulations demonstrated a balance between flowability and buildability, making them suitable for large-scale 3D printing applications. The findings of this study contribute valuable insights into the development of sustainable, alkali-activated binders for 3DCP. By maximizing the potential of LC2 through alkali activation, this research paves the way for cost-effective, environmentally friendly construction materials. The integration of such materials into 3DCP technology holds immense potential for advancing the future of sustainable infrastructure.

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Feasibility of Mine Wastes Stabilization for use as Pavement Construction Material

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Keywords: Pavement**,** alternative materials, stabilization techniques, geopolymerization, quarry dust, coal ash.

Abstract
Pavements are one of the most important infrastructural systems for economic development. However, the design of these pavements is often fraught with concerns such as the inadequate bearing capacity of the subgrade or the various layers to support the wheel loads imposed on them either at the construction stage or during their service life. Pavement construction relies heavily on natural materials, with 90% of aggregates coming from virgin sources or quarries. Developing nations face a shortage of high-quality materials, leading to two costly options: finding new quarries or using stabilizers like Portland cement (PC) and lime to enhance lower-grade materials. Although using PC and lime improves the mechanical qualities of low-grade natural construction materials, it is often associated with severe environmental consequences. Therefore, alternative materials and stabilization techniques in pavement construction are highly sought after. To narrow this gap, this study formulated a geopolymer binder using quarry dust (QD) and coal ash (CA) as pavement construction stabilizers. These materials were subjected to physio-chemical characterization using XRF, particle size analysis, and Atterberg limit test. Sodium hydroxide (NaOH) was used as an alkaline hardener in the geopolymerization process. The XRF results confirmed that QD and CA were primarily composed of SiO_2 and Al_2O_3, crucial for the cross-linking process providing strength to the geopolymer binder. Porosimeter results revealed all raw materials were mesoporous, indicating high reactivity for a more efficient geopolymerization process. The particle size distribution shows that these samples are predominantly fine aggregates, while the Atterberg tests indicate the samples as non-plastic and classified as A-3 soils according to the American Association of State Highway and Transportation Officials (AASHTO).
Key words: Pavement, alternative materials, stabilization techniques, geopolymerization, quarry dust, coal ash.

Introduction

Most of the world's developing countries have put sustainable development at the top of their agenda. One of the sustainable developments as reported by Nyangwara and Datche is the need to construct sustainable infrastructure such as roads. Mining of minerals (such as copper, coal, platinum, and gold) has been one of the major contributors to the economy of South Africa, making 60% of the contribution. However, the mining sector has contributed to major environmental contamination through the improper disposal of mine wastes. Mine tailings are among the most common waste products of mining operations. They comprise stone chips and dust of the parent rock from which they are extracted. There has been an increasing interest in the use of waste materials as stabilizing agents in recent years due to their good pozzolanic interaction with soil particles. Stabilization is an establishment remediation for contaminated soils and for hazardous waste. The techniques of stabilizing soil have been extensively used for improving the engineering properties of weak soil in civil engineering projects such as foundation bases, highway embankments, and road construction. Methods of stabilization and solidification of mining wastes using conventional cementing agents (i.e., cement and lime) have already been viewed in literature. Although the conventional approaches are reasonable from a mechanistic perspective, their application is incompatible with long-term sustainability. There are various stabilization techniques for mining wastes, which include incorporating them into a lime-cement mixture as pavement sub-grade material, synthesis of ceramisite, and phytoremediation, as a result, they're all appropriate for mine waste with minor sulphate minerals. This is because sulphate minerals in mine wastes produce highly acidic leachates which rapidly degrade cement-based products. The construction of roads uses large quantities of natural materials mostly mined from quarries such as laterites, cobblestones, and granites. The availability of natural construction materials is already scarce in some developing countries. However, the mining industry produces significant quantities of waste every year. Disposing of such a large volume of waste is not only expensive, but also causes a variety of environmental and ecological problems, including land occupation, windblown dust, contamination of surface and subsurface water, and tailing dam collapse. Therefore, using mine wastes as construction materials for roads could be a feasible solution to the problems mentioned above. Not only could it reduce the exploitation of natural construction materials in many parts of the world, but it could also reduce the cost of disposing and managing mine wastes. To use mine waste as a pavement material, either alone or in combination with natural materials, will require some stabilization. One of the first studies that addressed this problem might be the one by Sultan who investigated copper mine tailings (MT) stabilized with ordinary Portland cement (PC) as an alternative road construction material. The highest unconfined compressive strength (UCS) of 3.45 MPa was found at 8% of PC by the MT solid weight. The results showed that the PC stabilized MT has acceptable engineering properties and can be adapted to road construction. Swami et al. used 5% PC to stabilize kimberlite tailings for use in base and subbase layers. In this experiment, specimens were compacted using Modified Proctor to achieve an optimum moisture content and a maximum dry weight that met Indian Roads Congress Strength Specifications. Qian et al. investigated using quarry dust that had been stabilized with 5% cement as a road subbase layer. The stabilized specimens reached a UCS of 4.37 and 7.17 MPa after 7 and 29 days of wet curing respectively, which satisfied the strength requirement of stabilized road material specification. Most of the existing research looks at using PC or lime as stabilizers. Thus, the demand for more sustainable mining waste stabilization procedures with minimal environmental impact is a current challenge. One recent promising technique to simultaneously recycle and treat MT is called geopolymerization. Geopolymerization is an efficient stabilization process that creates an alternative to conventional binders. This procedure includes activating a precursor containing high amounts of amorphous aluminum silicates with an alkaline solution, resulting in a very stable substance called geopolymer with linked Silicon- Oxygen- Alumina- Oxygen-Silicon (Si-O-Al-O-Si) links. Geopolymer materials have several advantages over PC, including rapid development of mechanical strength, acid resistance, reduced expansion rate due to alkali-silica reactions, immobilization of toxic and hazardous matters, and reduction in emission of greenhouse gases when

prepared under optimum conditions. Although extensive research has been conducted on fly ash-based geopolymers for stabilizing soils and on recycled asphalt for road construction, studies of mine waste for road/pavement construction via geopolymerization of industrial wastes as binder/precursor remain very limited. Some mine wastes and processing wastes are ideal geopolymer materials because they contain high clay and aluminosilicate minerals, which are essential components responsible for the formation of geopolymer matrix. Aseniero et al. investigated an alternative road base material such as copper geopolymerized MT. It emphasizes the physical and mechanical characteristics of copper geopolymer MT. The results show that by properly selecting the materials and adequate preparation conditions (moisture content and NaOH concentration) and finally compaction copper MT can meet the strength requirements for road base by different state Department of Transport services (DOTs), and the Federal Highway Administration (FHWA) in the United States. Geopolymers are anticipated to be a suitable cementitious material for providing a stable aggregate base for pavements. According to the Detailed Rules for Highway Base Course Construction Techniques (JTG/T F20-2015), the stabilized road base course must meet requirements for sufficient strength, water stability, minimal shrinkage, and resistance to deformation. In this paper, fly ash/quarry dust-based materials are used to substitute the cement binder in the stabilized goldmine tailing. It discusses how mine wastes are stabilized together with alkaline hardener to form geopolymers. The physio-chemical properties and mechanical properties of this geopolymer material are studied to explore the feasibility of its application as a pavement construction material, thereby expecting to offer certain technical guidance in the application of fly-ash/quarry dust geopolymer in road engineering.
Cement and lime have been widely used in infrastructure as conventional binding materials for earth and rocks. However, their production consumes a lot of mineral resources, resulting in environmental pollution and excessive emissions of CO_2. At the same time, the secondary development and reuse of large quantities of industrial waste can provide a lot of raw materials for infrastructure construction. Geopolymer is an important type of nonmetallic cementitious material prepared by natural Si-Al materials or industrial wastes such as slag, fly ash, and/or steel slag. Compared with traditional Portland cement, geopolymer exhibit excellent characteristics, including early strength, high strength, low CO_2 emissions, excellent corrosion resistance, and durability. Therefore, many researchers use geopolymers to prepare mortar and concrete and strive to improve their properties.
Temuujin et al. used low-calcium fly ash as raw material to prepare geomeric, and by adding CaO and $Ca(OH)_2$ to the raw material system, the 28 d mechanical strength of the product increased from 11.8 MPa to 29.2 MPa. Kallempudi et al. carried out indoor experiments and found that with increased activator concentration and maintenance temperature, the compressive strength of low-calcium fly-ash-based geopolymer mortar was increased. Singh et al. studied the influence of activator concentration on the characteristics of fly-ash/slag-based geopolymer concrete. It was found that the development of compressive strength was earlier in geopolymer concrete than in ordinary Portland cement, and that it formed satisfactory bond with aggregates. Furthermore, with increased curing time, zeolite phase products played the leading role, resulting in minor drying shrinkage. Lahoti et al. studied the main factors that influenced the compressive strength of metakaolin-based geopolymer, which supports that the Si/Al (mole ratio) is the most important parameter, followed by Al/Na (mole ratio). The water cement ratio has less influence in the compressive strength of metakaolin-based geopolymer, differing from ordinary Portland cement. Wang et al. studied the change of fluidity and mechanical strength of geopolymers prepared with various water cement ratios. Results showed that the fluidity of geopolymers improved, but the mechanical strength decreased as the water cement ratio increased.

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GeoPCM: Lightweight PCM-enhanced geopolymer panels forupgraded building applications

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Keywords: geopolymer, perlite, phase change materials (PCM), thermal insulation, sustainable construction

The construction industry accounts for nearly 50% of global raw material consumption and 40% of total energy use. Additionally, it is responsible for over 35% of carbon dioxide emissions, with a substantial portion of energy consumption dedicated to maintaining thermal comfort within buildings. In response to these environmental challenges, numerous research initiatives are exploring the replacement of traditional cement with alternative materials derived from inorganic wastes, mine tailings, and industrial by-products through the process of geopolymerization. These geopolymers have garnered significant interest in the construction sector due to their potential to reduce emissions by up to 30% compared to conventional cement-based materials, aligning with the EU Green Deal's industrial decarbonization targets for 2030. Additionally, passive cooling and heating methods are being considered as optimal solutions to achieve indoor thermal comfort, reduce energy consumption, and promote healthier living environments.

This research introduces an innovative solution for advanced insulation materials, presenting PCM (Phase Change Material)-enhanced lightweight geopolymer panels that combine sustainable production with enhanced thermal performance. The geopolymer matrix, developed by MNLT Innovations IKE, is derived from recycled inorganic wastes, while perlite-PCM composites, consisting of an expanded perlite shell encapsulating paraffins, were developed by in.mat-Lab. These PCM-enhanced materials ensure low thermal conductivity and stable thermal comfort conditions while improving fire resistance compared to conventional microencapsulated PCM solutions. The products provide distributed thermal storage within the building structure, reducing reliance on active heating and cooling systems.

The experimental methodology included the preparation of lightweight additives which consist of perlite hollow spheres exhibiting a Loose Bulk Density (LBD) range of 50 – 90 kg/m3 and a particle size distribution of less than 1 mm. The commercial PCM employed was a RUBITHERM paraffin RT21HC. The optimum % PCM loading into the expanded perlite hollow spheres was determined by corresponding leakage tests, which reached 55 – 70 wt% depending on the LBD of the expanded perlite substrate. The geopolymer boards were formulated using an established geopolymer recipe with the addition of expanded perlite as reference and the expanded perlite/PCM composites. Specifically, the geopolymer precursors originated from SiO_2-rich industrial by-products of the glass industry. Furthermore, the mechanical properties and the curing regime of the geopolymer base formulations were enhanced by the addition of common low-cost additives such as ground-granulated blast furnace slag (GGBFS) and metakaolin. The geopolymerization was promoted by mixing the solid precursors with a NaOH-based alkaline activator.

The concentration of perlite-PCM composites in the geopolymer matrix was kept below 5 wt%. The composite formulations were optimized by fine-tuning the process parameters to produce low-thermal conductivity construction panels. Subsequently, the optimized formulations were upscaled to larger panels, and their thermal insulation performance was assessed under real-life atmospheric conditions. Pilot-scale test tests were conducted at EURECAT - Centre Tecnològic de Catalunya operational facilities to validate the thermal properties of the produced panels. A 3m x 1.5m test wall was assembled using reference

geopolymer panels and GeoPCM-enhanced geopolymer/PCM composite panels. The studied properties included heat flux, air and surface exterior and interior temperature, and air humidity.

A sustainability assessment was conducted by YS Cypriot Catalysts Ltd. (YSCC), focusing on a Life Cycle Impact Assessment (LCIA) to quantify the environmental and economic benefits of the new material. YSCC also led the standardization and market strategy, ensuring compliance with EN building material regulations. The results demonstrate that the GeoPCM material offers lower environmental impact, aligning with circular economy principles and EU sustainability targets.

This research focuses on three main objectives. First, optimizing perlite-PCM composites to maximize PCM loading and minimize leakage, while ensuring structural stability. Second, developing lightweight PCM-enhanced geopolymer panels, evaluating the impact of PCM content and geopolymerization on properties like porosity, mechanical strength, and thermal performance. Finally, scaling up production and validating material performance to ensure readiness for market deployment.

In conclusion, the GeoPCM project successfully developed a PCM-enhanced lightweight geopolymer panel, tested in an operational environment at TRL 7, demonstrating superior insulation properties, economic feasibility, and sustainability. The novel materials pave the way for cost-effective, energy-efficient, and environmentally friendly construction solutions, supporting industrial decarbonization and the transition toward sustainable building practices.

Geopolymers as Ammonia Sorbents: A Sustainable Solution for Air Purification

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Keywords: ammonia, fly ash, geopolymers, air purification, adsorption

Ammonia (NH_3) is a significant atmospheric pollutant, emitted primarily from industrial and agricultural activities, contributing to environmental degradation and adverse health effects. The development of effective sorbents for NH_3 capture is crucial to mitigate its impact and improve air quality. This study investigates the potential of fly ash-derived geopolymers as novel ammonia sorbents. These materials, commonly used in construction applications, exhibit promising adsorption properties that can be exploited for air pollution control. This research evaluates their adsorption capacity, desorption efficiency and suitability for practical use in air filtration system.

To evaluate the ammonia adsorption performance of geopolymer-based sorbents, a systematic experimental methodology was applied. The study was carried out using a special glass apparatus to prevent corrosion and ensure reliable measurements. The sorbents were subjected to several sorption-desorption cycles to determine their reusability and long-term stability. Adsorption experiments were performed at a constant temperature of 25°C under controlled conditions. Isothermal adsorption analyses were performed to derive essential parameters describing the sorption mechanisms and the sorption capacity of the geopolymers for NH_3. To evaluate the performance of the fly ash-based geopolymers, their adsorption capacity was compared with that of ZSM-5 zeolite. The fly ash used for geopolymer synthesis was derived from lignite coal, ensuring a sustainable approach to material utilisation.

The physicochemical properties of the synthesised geopolymers were investigated using advanced characterisation techniques. Specific surface area and pore structure analyses were carried out using the Brunauer-Emmett-Teller (BET) method and Barrett-Joyner-Halenda (BJH) method. Fourier transform infrared (FTIR) spectroscopy was used to identify the presence of functional groups contributing to NH_3 adsorption. X-ray diffraction (XRD) and scanning electron microscopy (SEM) provided insight into the structural composition and surface morphology of the materials. In addition, thermogravimetric analysis (TGA) was used to evaluate the thermal stability of the sorbents. Experimental results showed that fly ash-based geopolymers possess a significant NH_3 adsorption capacity, with the performance being influenced by their surface chemistry and porosity. The presence of active functional groups was found to enhance the interaction between NH_3 and the sorbent surface. The adsorption isotherms were described best by the Langmuir model, suggesting a monolayer adsorption behaviour and a high affinity of NH_3 molecules for the sorbent. When compared to ZSM-5 zeolite, the fly ash geopolymers showed competitive adsorption performance, further validating their potential as ammonia sorbents. Desorption studies showed that the

sorbents could be effectively regenerated under mild conditions, maintaining their adsorption capacity over multiple cycles. This reusability highlights their potential for integration into sustainable air purification systems. Furthermore, the incorporation of geopolymers into filtration units could provide an environmentally friendly alternative to conventional ammonia removal technologies.

The findings of this study contribute to closing the knowledge gap regarding ammonia adsorption on geopolymer materials. The use of fly ash geopolymers aligns with circular economy principles by repurposing industrial waste into functional materials. This research highlights the feasibility of utilizing geopolymers in air purification applications, addressing both environmental pollution and waste management challenges. Future research efforts will focus on optimizing the composition and activation process of geopolymers to enhance their adsorption properties and evaluating their performance in real-world conditions. The scalability of these materials will be explored to facilitate their widespread adoption in industrial and agricultural settings. The results obtained in this study provide a solid foundation for the development of advanced ammonia sorbents, supporting ongoing environmental initiatives aimed at reducing atmospheric NH_3 levels. By improving the efficiency and sustainability of air purification technologies, the integration of geopolymer-based sorbents represents a significant step toward mitigating ammonia pollution and enhancing air quality.

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Impact of blending and pretreatment of kaolinitic clays co-calcined with alkali and alkali-earth metals on metakaolin properties

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Keywords: Co-calcination, blending, kaolin, alkali and alkali-earth metal, supplementary cementitious materials.

Cement production is a major source of carbon emissions due to the high-temperature decomposition of limestone to produce clinker. Reducing clinker content is a direct strategy to lower emissions and mitigate the environmental impact. Supplementary cementitious materials (SCMs) have been studied for this purpose. They replace part of the cement while enhancing strength and durability. Calcined clays, particularly metakaolin (MK), are well-known SCMs. MK is a partially disordered aluminosilicate that exhibits pozzolanic reactivity and forms upon activation of kaolinitic clays. These clays are of interest due to their abundance and presence in industrial waste streams such as mine tailings and dredging sediments.

The level of clinker replacement depends on the reactivity of the MK, which is influenced by the chemical and mineralogical composition of the raw material, among other factors. Clays containing between 40 and 60 wt% kaolinite have been considered most suitable. This range enables significant reactivity while mitigating workability issues due high surface areas correlated with higher kaolinite concentrations. Given the potential of low-grade kaolins, a deeper understanding of impurity effects could expand usable materials. Avoiding negative interactions or leveraging synergies would significantly enhance MK production and enable higher clinker replacement.

In this context, co-calcination of kaolinitic clays with alkali and alkali-earth metals (AAEMs) has been explored. Evidence shows that co-calcining kaolinitic clays with NaOH between 600 °C and 850 °C alter the MK composition and structure, improving its pozzolanic reactivity. Notably, an increase in reactivity was observed for a clay with a kaolinite content below 40 wt% when co-calcined with 2.5 wt% NaOH at 600 °C, compared to the calcined system without alkali addition. Some studies conclude that kaolinite co-calcination with calcite affects the MK with some reporting lower while others higher reactivity. These results highlight the influence of AAEMs on SCM performance but do not clarify interaction mechanisms or the impact of different AAEM compounds and pretreatment methods.

The choice of AAEM compound is critical, as factors like decomposition temperature influence cation interactions during co-calcination, potentially limiting AAEM availability during kaolinite dehydroxylation and amorphization. Differences in material pretreatment may also explain inconsistencies, leading to conflicting conclusions among previous studies. A better understanding of pretreatment effects could improve process scalability and ensure consistent laboratory results in clay activation. Consequently, this study documents phase composition changes and MK aluminosilicate structure evolution during kaolin-AAEM co-calcination under different pretreatment approaches.

A clay (80 wt% kaolinite) was mixed with 2, 5, and 10 wt% of cation in Na_2CO_3, KOH, $Mg(OH)_2$, and $Ca(OH)_2$ and co-calcined at 650 °C and 750 °C in a box furnace. Figure 1 summarizes the methodology.

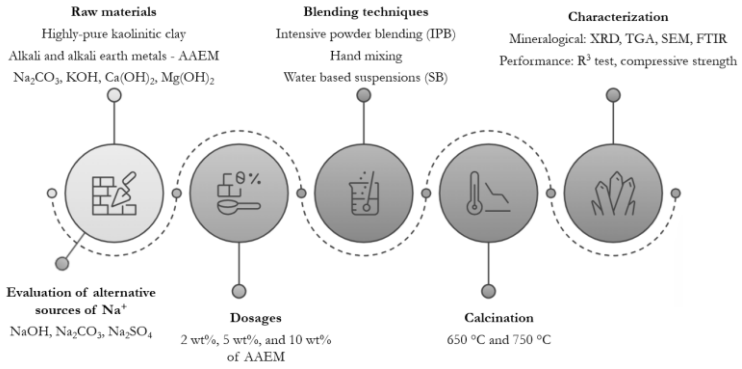

Figure 5. Methodology used for this research.

The materials were blended in different ways. Intensive powder blending (IPB) was done on a roller bench for 48 hours. Hand-mixing was done by blending the powders with a spatula directly in the crucible. Additionally, to ensure a very homogeneous blend, suspensions (SB) were prepared in a high intensity mixer at a water-to-solid ratio of 0.5 and dried at 105 °C overnight. To assess the Na source effect, IPB samples with 5 wt% Na_2CO_3, NaOH, and Na_2SO_4 were co-calcined at 750 °C. The co-calcined materials were characterized by X-ray diffraction (XRD) with Rietveld refinement for quantitative phase composition. Dehydroxylation was assessed through thermogravimetric analysis (TGA), while the depolymerization of the aluminosilicate network was studied using Fourier Transform Infrared Spectroscopy (FTIR). Selected samples were analyzed using scanning electron microscopy (SEM). The R^3 test and compressive strength measurements were used to assess the reactivity and performance of selected samples.

The results highlight the strong influence of the blending technique on the mineral assemblage, with each approach yielding distinct compositions. A key difference in mineral phase evolution was linked to cation charge: XRD and SEM showed that monovalent cations primarily formed feldspars, while divalent cations favored free oxides. FTIR analysis showed peak shifts near 1050 cm^{-1}, associated with structural changes of the MK for Na^+ and K^+, but not for Mg^{2+} and Ca^{2+}. Higher Na^+ and K^+ additions shifted the peak to lower wavenumbers, indicating greater aluminosilicate depolymerization or incorporation of Al^{3+} in the silicate network. However, higher reactivity occurred with lower alkali additions, except for $Mg(OH)_2$, where reactive MgO interfered in the R^3 reactivity appraisal. While reactivity trends remained consistent across blending methods and AAEM additions, absolute values were significantly affected. SB showed reactivity 50–80 J/g SCM lower than IPB, associated with a more homogeneous distribution of cations that enhanced formation of feldspars. SB yielded more consistent results, allowing to directly associate the results on reactivity to the evolution of the mineralogical phases. SB also provided more accurate and reliable data for low AAEM additions.

Overall, the study helps to come to more consistent experimental results as a starting point for development and optimization AAEM-clay co-calcination and can also explain some of the disparities observed in the literature so far.

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Impact of waterglass dosage and steel slag content on alkali activated materials using response surface methodology

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Keywords: Alkali activated materials, Steel slag, Flowability, Alkali dosage, Response surface methodology.

Steel slags are generated in massive amounts due to the expansion of steel industry leading to increased landfill volume and posing an environmental hazard from leaching of harmful substances (e.g. heavy metals). While the large content of CaO, among other oxides, render them suitable for alkali activation, it also presents a challenge for workability and setting behaviour of alkali activated materials. In this study, two key parameters, namely, potassium waterglass (K-WG) dosage and Basic oxygen furnace slag (BOFS) content, affecting the fresh and hardened properties of metakaolin-based alkali activated paste were simultaneously explored. Central composite design (CCD) and response surface methodology (RSM) were employed to explore the interaction between the two factors as well as the significance of each individual factor on fresh and hardened properties of pastes. CCD and RSM are particularly convenient when investigating properties (i.e. response) influenced by multiple parameters capturing the interaction between them and allowing for defining the optimal conditions. Three levels were defined for each of the investigated factors, with the values of 28, 33, and 38 wt.% for K-WG dosage and 22, 28, and 33 wt.% for BOFS content (wt.% of the total mix mass). Accordingly, CCD yielded nine mix compositions covering all possible combinations between the levels of each factor.

The primary response of interest was the flowability loss which was investigated by the repetitive measurement of the spread flow over a maximum of 50 min (after mixing), with 10 min intervals between individual measurements. the slope of a linear fit of the spread flow measurements of each mix was defined as the rate of flowability loss. In addition, initial setting time, 2 and 28-day compressive strength, and rate of strength gain were examined. Response surfaces were generated using linear models, incorporating interaction terms where statistically significant. Except for the rate of strength gain, the statistical analysis of the generated response surfaces of all other properties had high adjusted R^2 ranging from 0.86 to 0.93 implying the adequacy of the linear model. Interaction term was found to be insignificant for all properties, except for the flowability loss, which exhibited a clear interaction with a magnified flowability loss rate with decreasing K-WG dosage and simultaneously increasing BOFS content. Surprisingly, compressive strength negatively correlated with the flowability loss rate (i.e. the higher the flowability loss rate the lower the strength). Thus, mixes with the highest and lowest flowability loss rates had 28-day strengths of 43 and 81

MPa, respectively. In general, while both investigated factors had a clear effect on responses, K-WG dosage was found to be statistically more significant than BOFS content. For strength gain rate, the generated model was insignificant implying no influence of both factors on this response.

As a second step, three mixes, with a fixed BOFS content of 33 wt.% and varying K-WG dosage, were selected for further investigation using isothermal calorimetry, ATR-FTIR spectroscopy, and XRD at 28 days. These mixes were of interest as they displayed the highest flowability loss rate. The results of the isothermal calorimetry showed different levels of heat release but similar heat flow trend while ATR-FTIR spectra suggested lower extent of the formed C-A-S-H with lower K-WG dosage. Simultaneously, higher tendency for carbonation with lower K-WG dosage was observed in ATR-FTIR spectra and XRD patterns. The insignificant effect of the investigated parameters on the strength gain rate, combined with isothermal calorimetry results, ATR-FTIR and XRD, suggests favourable dissolution kinetics of BOFS calcium-bearing phases at low levels of K-WG dosage. This likely leads to the quick precipitation of C-A-S-H increasing the volume of solids affecting the ongoing development of the microstructure.

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Influence of Concrete Surface Type on the Bond Strength of Geopolymer Adhesive

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Keywords: Geopolymer adhesives, bond strength, tensile tests, torsion test

Geopolymer binders have gained attention as sustainable alternatives for enhancing the durability of concrete structures, particularly in aggressive environments such as sewer systems where ordinary Portland cement (OPC) concrete is prone to degradation in acidic conditions. In such applications, a geopolymer layer can be applied as a protective coating over OPC concrete, forming a composite system. However, the effectiveness of this composite depends on its bond, which is strongly influenced by the surface characteristics of the underlying concrete. While geopolymers offer excellent chemical resistance and mechanical stability, their ability to bond effectively with OPC concrete under different surface conditions remains an area requiring further investigation. Therefore, this study focuses on evaluating the tensile and shear adhesion of geopolymer adhesives by investigating the adhesive bond strength under different surface roughness levels and various surface pre-treatments. A better understanding of interfacial properties is essential for optimizing the use of geopolymers as protective layers in infrastructure applications exposed to harsh environments.

In this study, cylindrical drill core concrete samples were utilized to assess the bond strength between geopolymer adhesives and standard OPC concrete with varying surface conditions. To ensure a uniform adhesive layer, the drill core specimens were bonded to steel cylinders using epoxy resin. A geopolymer mortar, composed of metakaolin and slag-based binders, was cast between two drill core specimens, forming the adhesive interface. To prevent drying shrinkage of the geopolymer adhesive, a waterproof wax spray was applied, and the middle section containing the geopolymer mortar was sealed with plastic foil. Three fundamental surface types were examined: smooth, porous, and roughened (Fig. 1). The smooth surface represents concrete with a higher water-to-cement ratio (w/c), resulting in a dense and low-porosity surface. The porous surface originates from a lower w/c, leading to a highly porous surface. The roughened surface was obtained by sand/shot-blasting porous concrete, which smoothed out sharp aggregate edges and created a more uniform surface profile. Additionally, two pre-treatment methods were applied to the porous concrete: wet-saturation (as a primer) and activator application (as a primer).

Uniaxial tensile tests were performed on specimens at 28 days of age using a 400 kN universal testing machine, applying a controlled force of 0.4 kN/s until failure. The results showed significant variations in tensile bond strength depending on surface preparation. The highest tensile bond strength was observed for the porous surface (3.83 N/mm²), followed by the smooth surface (2.68 N/mm²). The roughened surface (2.63 N/mm²) exhibited slightly lower bond strength, suggesting that surface roughness alone does

not necessarily enhance adhesion. In this case, the sand-blasting process applied to the porous surface re-shape porous surface by rounded sharp aggregate edges, leading to a more uniform but less interlocked surface structure, which may explain the decrease in adhesion. The porous surface with a wet primer (1.82 N/mm²) had reduced bond strength, suggesting that excessive moisture weakened the interface. The porous surface with an activator (0.03 N/mm²) showed the lowest bond strength, indicating a negative impact of the activator treatment. These results emphasize the role of surface porosity in optimizing bond strength while demonstrating that additional treatments, such as moisture exposure or activator (containing 35% water by weight), can reduce adhesion by increasing water content and altering the bonding mechanism.

To further investigate the mechanical behavior of the best-performing surfaces, torsion tests were conducted on the smooth and porous concrete specimens. A 5 kNm torsion testing machine was used, incorporating three cardan joints to minimize normal forces and misalignment effects. A suspension system was also employed to reduce bending moments and shear stresses induced by the sample's own weight and the cardan joints. The torsion tests revealed that both smooth and porous surfaces provided strong resistance under torsional loading. The shear stress values obtained were 2.17 N/mm² for smooth concrete and 2.04 N/mm² for porous concrete, confirming that while smooth surfaces exhibited slightly higher resistance, porous surfaces still maintained high adhesion strength.

The findings demonstrate that the surface characteristics of the concrete substrate play a crucial role in bond strength. Porous concrete, with a low w/b ratio, contained air voids, enhancing mechanical interlocking and leading to the highest adhesion strength. Smooth surfaces behave similarly; however, due to the higher w/b ratio, the pores are much finer, which also improves adhesion. Sand/shot-blasting reduced deep voids and smoothed aggregates, lowering interlocking efficiency, explaining its lower adhesion. Additional treatments, such as activators and excessive moisture, negatively impacted bonding, reinforcing porosity as more influential than roughness. Torsion tests confirmed that both smooth and porous surfaces provide strong shear resistance, making them suitable for structural applications. Future studies should explore microstructural interactions and long-term durability.

(a) (b) (c)

Figure 6. Surface types: (a) smooth, (b) porous and (c) roughened

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Influence of Treatment Methods on Properties and Performance of MSW Incinerated Bottom Ash as a Supplementary Cementitious Material

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Keywords: Supplementary Cementitious Material, MSW Incinerated Bottom Ash, Treatment Methods

A significant portion of the residual municipal solid waste undergoes incineration, producing substantial amounts of residual ashes known as Municipal solid waste incinerated bottom ash (MSWIBA). Norway alone produces approximately 300,000 tons of MSWIBA every year. Several studies indicate that the MSWIBA can be utilised as a supplementary cementitious material or an aluminosilicate precursor in an alkali-activated binder. However, significant challenges include the presence of elemental aluminium and the high presence of alkali salts. The treatment methods discussed often face criticism by the industry for their lack of industrial feasibility. Also, there has been no comprehensive study on the effect of treatment methods on the performance of MSWIBA-based binders. This work compares the influence of various treatment methods on the properties and performance of MSWIBA-based binder material. The treatment methods that are industrially feasible, both economically and environmentally, have given focus. It includes selective screening, dry and wet sieving, dry and moisture grinding, hot water baths, mixing with slag, etc. A replacement level of 30% has been used. The impact of treatment methods on the presence of elemental aluminium, pH, and chemical composition was examined. Mortar compressive strength tests have been carried out at early and later ages to understand the effect of treatment methods on the mechanical performance of IBA. Isothermal calorimetry has been used to understand its impact on early-age hydration kinetics. X-ray diffraction and Rietveld analysis were carried out to understand the effect of treated IBA on phase assemblages and clinker hydration. The study outlines the most feasible ways to develop IBA as a supplementary cementitious material and its impact on hydration kinetics, phase assemblages, and mechanical performance.

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In-situ analysis of the reaction mechanisms governing the formation of alkali-activated slag cement

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Keywords: Alkali-activated materials, in-situ analysis

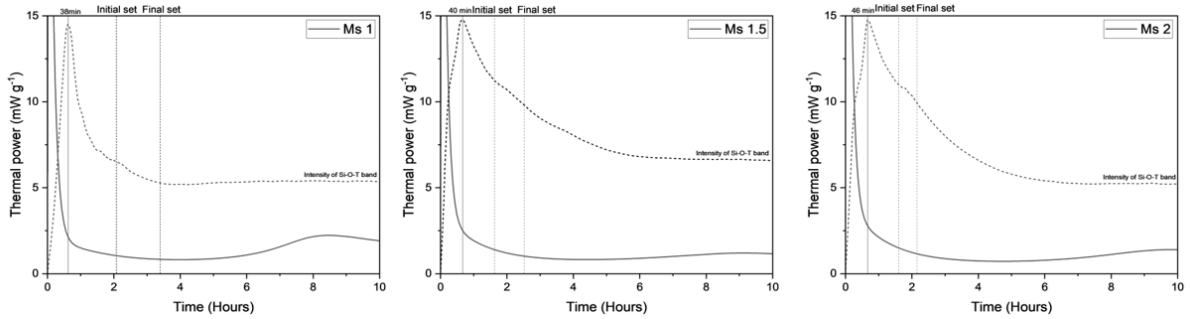
Cement is the glue in concrete, the second most consumed resource globally, after water. A global modern necessity, its usage is forecast to rise 25% by 2050. Unfortunately, concrete and cement production is also linked to large CO_2 emissions. Annually, 8% of global CO_2 emissions come from the cement production, and for every tonne of Portland cement (PC) produced, almost a tonne of CO_2 is released. This creates the paradoxical task of needing to severely reduce emissions whilst greatly increasing output to meet future demand.

Replacement of PC with a low-carbon alternative is one method of reducing the environmental cost of cement usage. Alkali-activated cements (AACs) are a major low-carbon alternative to PC, and are made from an aluminosilicate precursor, such as industrial slags or fly ash, which is 'activated' by a strong alkali component in the presence of water. A key phase in this cement is the C-A-S-H gel, characterised by the Si-O-T bonding environment (T = tetrahedral Si or Al). The product formed is analogous to PC, however the reaction mechanisms occurring in these cements under different conditions are not completely understood. The aim of this research is to develop a comprehensive mechanistic understanding of the formation of AAC pastes by analysing the reaction kinetics, thermodynamics and final products, by altering mix design and cement formulations.

In-situ analysis of the formation of silicate alkali-activated slag cement of varied SiO_2/Na_2O ratios (modulus) was undertaken via isothermal calorimetry and diffuse reflectance infra-red spectroscopy (DRIFTS). This novel application of DRIFTS has enabled the progress of the formation of specific infra-red active bonding environments present in the cement to be followed. The observed results show rapid growth followed by shrinkage of the Si-O-T bonding environment. This is observed in the DRIFTS spectra as the variation of the intensity of the Si-O-T infrared band, with a maximum intensity always occurring around the first 40 minutes, followed by a period of reduction. The intensity of this band stabilises to around 50% of the maximum after around 6 hours. This unexpected observation is attributed to the rearrangement of the silica polymer chains within the cement gel. Vicat tests were carried out on the samples, allowing for the initial and final setting times of the cements to be measured. It was found that the setting time of the cement was reduced at higher moduli. Furthermore, when aligned to the intensity of the Si-O-T over time, gathered by DRIFTS, it is evident that the rate in which the band reduces in intensity changes upon the initial set. This verifies that the DRIFTS method works on both pastes and hardened cement, and suggests that the Si-O-T bond formation directly affects the setting of the cement.

The calorimetry shows a significant exothermic peak occurring after an induction period in each formulation, with this acceleration stage becoming more retarded as the modulus is increased. Interestingly, the timing of this acceleration gathered by the calorimetric data does not correspond with any significant band shifts in the DRIFTS data, suggesting that the formation of the Si-O-T bonding environments is independent of heat output. Solid state ^{27}Al, ^{29}Si and ^{1}H NMR has been undertaken on the samples, enabling the gel structure at different timepoints in the reaction to be directly compared. These timepoints have specifically been chosen based on the calorimetric data, allowing for a detailed description of this

exothermic events to be described. A further piece of the puzzle will be completed by in-situ XRD, which is currently being optimised.



This work has demonstrated the application of in-situ DRIFTS, a novel spectroscopic technique in cement characterisation. The compilation of all of the gathered data allows for a rich picture of the processes governing the formation of alkali-activated slag cements to be built up, including how the Si-O-T bonding environments present in the material change as the reaction progresses. Further study into the area is continuing, with the ultimate aim of increasing our knowledge of these new sustainable materials, enabling their application in the real world.

Figure 7- DRIFTS (dashed black line), Vicat and calorimeter (solid green line) data of the 3 cement formulations, of moduli 1, 1.5 and 2, overlayed.

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Low alkaline one-part geopolymer hemp-shiv composites as a potential insulation and acoustic board

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Keywords: one-part geopolymer, hemp-shiv, sound absorption coefficient, acoustic board, thermal conductivity

Geopolymer is produced by reacting aluminosilicate-containing materials with liquid alkali and alkali silicate in a traditional two-part process. However, large-scale production of geopolymer using this method faces challenges related to the viscosity and handling of alkaline solutions, which are corrosive and hazardous. One-part geopolymers, formulated by blending solid aluminosilicate precursors with solid alkaline activators, may present a viable alternative to the two-part system. However, traditional activators such as Na_2SiO_3 and NaOH are costly and have a significant environmental footprint due to the energy-intensive production and transportation processes, making large-scale use of these activators impractical. Rice husk ash presents a viable alternative to Na_2SiO_3. Rice husk ash is composed of nearly 90% silica. It has a porous, lightweight structure with a density ranging from 83 to 125 kg/m³ and a notably high surface area. Therefore, the primary aim of this study was to investigate a novel composite of one-part fly ash (FA) geopolymer combined with hemp shiv. Rice husk ash (RHA) was used as an alternative source of silica to replace FA, and sodium hydroxide (NaOH) was employed as the alkali activator at a low concentration to reduce the environmental impact of the alkaline solution. Hemp shiv (HS) was incorporated as a lightweight aggregate in volumes ranging from 40% to 70%. The HS, meticulously cut and sieved to obtain particles ranging from 4.75 mm to 300 μm, was sourced from a local hemp farm in Thailand. Class C (21% CaO) was used as the alumino-silicate source. RHA was used to replace 2.5% by weight of fly ash (FA). The water-to-binder ratio was set at 0.35. Sodium hydroxide (NaOH) powder served as the alkali activator, with the NaOH-to-water ratio corresponding to a solution concentration of 3 M.The study evaluated the composites' mechanical, thermal, and sound absorption properties, supported by thermogravimetric analysis (TGA) and X-ray diffraction (XRD) characterizations. Cylindrical samples with a diameter of 60 mm and a length of 120 mm were tested for compressive strength according to ASTM C39,. For assessing flexural strength, prism-shaped samples measuring 40×40×160 mm were subjected to a three-point bending test, following ASTM C78-02. Bulk density and permeable porosity were determined following the procedures specified in ASTM C140-99 and ASTM C642-97, respectively. The sound absorption coefficient (SAC; α) was determined using the ASTM C384-04 standard (Standing Wave Tube Method). Thermal conductivity testing was performed using the Hot Disk TPS2500 instrument, following the transient plane heat source method as described in ISO 22007-2. The results indicated that increasing the HS content led to a reduction in compressive strength. Flexural strength declined, ranging from 0.65 MPa at 40% HS to 0.01 MPa at 70% HS. Concurrently, higher HS content resulted in increased porosity and improved sound absorption. The composites demonstrate low thermal conductivity, ranging from 0.307 to 0.187 W/m·K, making them promising for use as efficient building insulation materials. Notably, the 50% HS composite meets the minimum requirements for decorative acoustic boards, achieving a noise reduction coefficient (NRC) of 0.4. Thermogravimetric analysis (TGA) reveals the decomposition of additional phases in the one-part geopolymer, including C-A-S-H, $Ca(OH)_2$, and Na_2CO_3, which are not present in the conventional two-part geopolymer systems. These findings underscore the unique properties and potential applications of the one-part FA geopolymer-hemp shiv composites.

Mechanical and Microstructural Performance of Carbon Sequestered Geopolymer Stabilized Laterite Soil under Outdoor Exposure

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Keywords: laterite soil, long-term performance, durability, Carbon capture, soil stabilization.

Abstract – Geopolymer materials have gardened considerable interest for their potential to capture and store carbon dioxide. However, the implementation of accelerated carbon sequestration requires further research on its durability, for instance long-term outdoor exposure conditions. The influence of atmospheric carbonation and environmental factors from outdoor exposure on the microstructural and mechanical properties of carbon sequestered geopolymer is rarely reported. In this manuscript, the impact of 1-year outdoor exposure on the mechanical and microstructural performance of carbon sequestered geopolymer stabilized laterite clayey soil is investigated. The accelerated carbon sequestered geopolymer specimens are exposed to outdoor conditions like natural carbonation, rainwater ingress, repeated wetting and drying, and weathering. The findings demonstrate that accelerated carbon sequestration of geopolymers can lead to severe decalcification and formation of carbonate minerals, for example: sodium carbonate and calcium carbonate salts. Exposing the geopolymers to rainwater leads to leaching of soluble sodium carbonate minerals. Further, the repeated cycle of wetting and drying increases the vulnerability to natural carbonation. It accelerates the coarsening of pore structure and decalcification of binding gel. Geopolymers without laterite soil exhibit a 2.6-times increase in pore volume (pore diameter 10-100 nm) compared to 1.25-times increase in laterite soil-based geopolymers due to accelerated carbonation. compressive strength of the geopolymers is reduced by 25-40% due to further exposure to 365-days of natural carbonation in outdoor exposure conditions. Therefore, more research is required to fully explore the prospective application of accelerated carbon sequestration in geopolymer stabilized laterite clayey soil in outdoor exposure.

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Mechanical Performance of Electric Arc Furnace Slag-based Alkali activated paste using a one-part geopolymer technique.

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Keywords: Electric arc furnace steel slag; alkali-activated material; Supplementary cementitious materials; one-part geopolymer.

The emission of greenhouse gases has surfaced as a prominent environmental issue, with infrastructure development identified as a principal factor contributing to this phenomenon. Furthermore, the swift progression of industrialization has mandated the utilization of resilient, sustainable, cost-effective materials with fire-resistant properties. Steel, a material with high demand for infrastructure undertakings, is predominantly produced through the Blast Furnace (BF) and Electric Arc Furnace (EAF) processes. The BF process represents a conventional technique of steel fabrication. It depends on using iron ore, coke, and limestone, whereas the EAF process primarily employs recycled scrap steel. Moreover, the BF process is characterized by its substantial energy consumption necessitated by the elevated temperature requirements, in contrast to the EAF process, which is typically more energy-efficient as it utilizes electricity to melt scrap steel.
To adequately confront the pressing imperative of attaining net zero emissions and diminishing the environmental footprint, a transformative transition from the traditional Blast Furnace (BF) methodology to the Electric Arc Furnace (EAF) methodology is indispensable. Nevertheless, this shift results in an augmented generation of EAF slag (a by-product of the EAF process) frequently relegated to landfills. Notwithstanding its inherent potential, the presence of free lime obstructs its applicability as an additive in cementitious products. Conversely, it is a promising precursor for alkali-activated materials (AAMs) owing to its elevated calcium and silica content. These materials demonstrate comparable physio-mechanical characteristics to traditional cementitious materials. This article underscores the application of EAF slag as a precursor for AAMs, which presents a significant opportunity to curtail waste production, advance circular economy principles, and provide a more sustainable alternative to mitigate the greenhouse gas emissions linked to cement manufacturing.

Alkali-activated materials (AAM) are increasingly acknowledged as viable substitutes for ordinary Portland cement (OPC) in efforts to mitigate CO_2 emissions and transform various waste products into valuable resources. In contrast to their counterparts that utilize concentrated aqueous alkali solutions, the advancement of "just add water" one-part alkali-activated materials (OP-AAM) has garnered significant interest, primarily due to their advantages in alleviating the hazardous, irritating, and corrosive characteristics associated with activator solutions.

The EAFS was acquired and subjected to an extensive characterization process, which included the evaluation of its chemical composition, particle size distribution, and mineralogical characteristics. The Class F Fly ash modifier was systematically substituted in increments from 0% to 75% (by weight) in steps of 25%. The activator-to-precursor content ratio was worked within 6% to 12% (by weight). Furthermore, the sodium silicate to sodium hydroxide ratio within the activator combination was modified between 1.0 and 3.0. The water-to-solid ratio also ranged from 0.15 to 0.25. The Taguchi design of experiments (DoE) methodology was utilized to investigate the implications of these mixed design parameters. The experiment began with the dry mixing of the precursor, modifier, and activator utilizing a Hobart mixer to ensure

uniformity, followed by incorporating water; the alkali activation process was started. The resulting samples were then cured for 28 days under ambient conditions. A series of tests and analyses were used to assess the AAMs' fresh, hardened, and residual behaviour, in addition to their durability and microstructural properties.

Flow loss of fresh paste, shrinkage strain, initial and final setting time, water absorption, and compressive strength were measured. Results indicated that the flow loss in alkali-activated paste and compressive strength development significantly depended on the proposed alkali quality coefficient. Due to irregular particles and higher CaO content in EAF, results show lower initial flow and a higher rate of flow loss. Initial and final setting times have varied between 25-150 and 75-220 min, respectively. A higher rate of compressive strength development is achieved at a later age for EAF: FA-based alkali-activated paste. The compressive strength was observed for L16 trial mixes at 25°C. The mix of 75% EAFS and 25% fly ash shows the best results at ambient temperature compared to the other mixes. The compression strength varied in the range of 20-40MPa (at 28 d, ambient temperature and relative humidity 95%). In addition, the results reveal that the optimum percentage of activator was 8% by the weight of precursor, giving the highest physio-mechanical properties. The compression strength value of hardened paste proved that the slag activation continues after adding water. The activated slag paste was characterized using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and Scanning Electron Microscopy (SEM) techniques. The results of the different analyses are in good harmony with those of mechanical properties and prove that one-part geopolymer can be beneficially used as an alternative to conventional cement.

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Mechanical strengths mix design approach and microstructure of slag/glass powder green mortars

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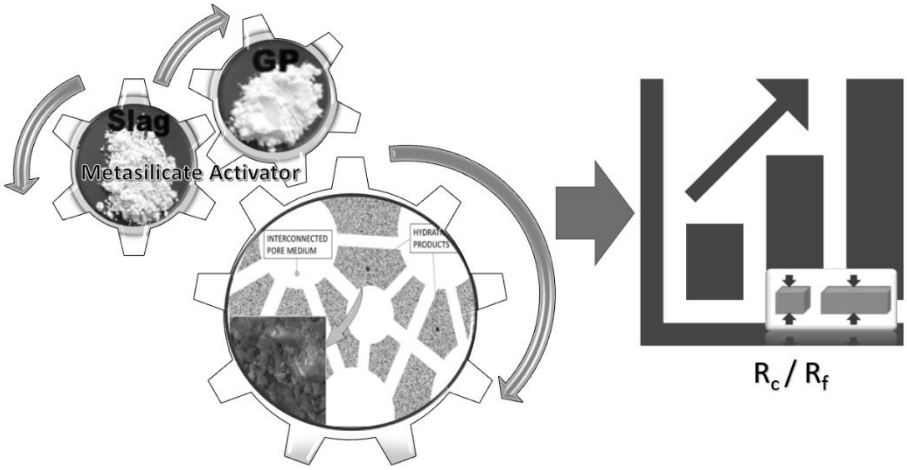

Keywords: Alkali-Activated mortars, slag, glass powder, microstructure, mix design, mechanical strengths

With the growing awareness about the harmful impacts of global warming on planet and human beings we see flourishing sustainable solutions and initiatives by researchers, engineers and public associations. Hence in construction sector, one of the most carbon emissions sources geopolymers and alkali-activated materials (AAMs) knew a great jump and consideration since Davidovits' works. Thus, research is *en route* to afford more efficient waste-based AAMs. Even their high properties, AMMs are reported to have some shortcomings like mix design, workability, and some long-time properties.

Glass powder (GP) as urban waste, with abundant daily production worldwide, represent a challenging issue for municipal managers. Thus, after several works on ordinary Portland cement/glass powder mixtures, it seems to be that its inclusion in AAMs is a good solution to avoid its weak reactivity and alkali silica reactions.
So, the main aim of this work is to optimize AAMS mix design and to assess their mechanical and microstructure properties.

The work methodology was based on an optimizing approach with JPM and Designer Expert software on 12 AAMs mortar mixtures. Actually, we carried out a basic experimental design with two variables and two responses. The first variable parameter concerned the precursor glass powder content replacing slag

(with 4 levels: 0, 20, 40 and 60 % by weight). The second was silicate to sodium ratio of the activator Ms= SiO_2/Na_2O, with tree values: S1 solution with Ms=0.5, S2 with Ms=1 and S3 with Ms=1.5. The measured responses were compressive and flexural strengths (Rc and Rf) at early age (3 days) and conventional (28 days).

The liquid to solid ratio of all the mixtures was kept equal to 0.4. Mortars mixes had a sand/powder mass ratio of 2.75. To prepare the metasilicate solution we mixed NaOH and Na_2SiO_3 to achieve the desired Ms.

The mortar samples were tested, according to EN 196-1/2016 standard, for compressive and flexural strength at 3 and 28 days on 4x4x4 cm^3 cubes. Also, appropriate S2 size samples were observed through SEM device associated with an EDS elementary analysis (Gemini 300 ZEISS equipped with the Quantax 10 Bruker X-ray microanalysis detector).

The main results of the study were: Mechanical strengths of AMMs are higher known values of ordinary Portland cement mixtures. However, a slight drop of compressive strength with higher GP substitution was observed; 20% GP was found to be the optimum mix regarding compressive and flexural strengths; correlations between compressive and flexural strength for AAMs is very close of OPC's one; the activated mixtures present a high compressive strength at early hydration age greater than 30 MPa; well refined microstructure was observed into 28 days samples.

It seems that a 20% glass powder rate may be recommended for slag-based AAMs to get strong and durable mixtures, especially for concreting controlled industrial applications (ex: precast elements) , and for structural elements where 50 MPa is generally required.

So, the finely crushed glass powder, under 80µm, is a more environmentally friendly for activated materials, which can may very reactive in a chemically activated material and leads to performed properties through different applications.

We recommend hence AAMs formulae for industrial precast and ready-mixed concrete for applications in civil construction and engineering works.

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Phase-Driven Microstructure Refinement in Geopolymers Enabled by Copper Slag-Based Core-Shell Structure

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Keywords: Geopolymer; Nano-silica; Core-shell structure; Copper slag

Geopolymers, emerging as sustainable low-carbon alternatives to ordinary Portland cement (OPC) with 60-70% lower CO_2 emissions and 30–50% reduced energy consumption, face significant limitations in load-bearing applications due to their intrinsically low elastic modulus (typically 15-25 GPa, 20-30% below OPC) and high porosity (25-35%). These deficiencies originate from the weak sodium aluminosilicate hydrate (N-A-S-H) gel phase, characterized by low silicon-oxygen tetrahedra polymerization, and a detrimental feedback loop between gel weakness and pore defects. Conventional enhancement strategies such as rigid particle fillers (e.g., copper slag (CS) with Mohs hardness≈7.5, which physically fills pores but exhibits interfacial inertness) or nanomaterial additives (e.g., nano-silica (NS), which chemically enhance gel polymerization but cause agglomeration and localized porosity) fail to resolve these intertwined challenges concurrently. Hybrid systems blending N-A-S-H and stiffer calcium aluminosilicate hydrate (C-A-S-H) gels offer partial improvement but remain constrained by inherent N-A-S-H limitations. To overcome this limitation, a copper slag-based core-shell composite (CS@PVP@NS) is innovatively designed and synthesized using industrial CS waste through a sustainable acid-leaching and complexation process. The composite features an iron-rich CS core for mechanical reinforcement and a high-reactivity NS shell (specific surface area 358 m^2/g, synthesized from CS via acid leaching) bonded via polyvinylpyrrolidone (PVP). PVP acts as a multifunctional mediator: its carbonyl groups form coordination bonds with Fe^{2+} on CS, while hydrogen bonding (e.g., SiO_2–OH···N–H) and steric hindrance ensure uniform, agglomeration-resistant NS encapsulation. Scanning electron microscopy (SEM) confirms the successful formation of a continuous 0.6 μm-thick NS shell fully encapsulating CS cores, with energy-dispersive X-ray spectroscopy (EDS) mapping verifying elemental gradients consistent with core-shell architecture. Incorporating just 2 wt.% CS@PVP@NS into fly ash/slag geopolymers optimizes reaction kinetics, delaying early exothermicity while promoting prolonged gel formation. Microstructurally, the rigid CS core physically reduces harmful macropores (>100 nm) by 8.13%, while the NS shell nucleates dense gel growth, yielding a nano-mesoporous network with only a 0.43% net porosity increase. Meanwhile, SEM observations demonstrate that the core-shell structure effectively reduces crack propagation paths through enhanced interfacial bonding. Chemically, the NS shell facilitates Al^{3+} substitution for Si^{4+}, driving a phase transition from weakly polymerized N-A-S-H to highly crosslinked C-A-S-H gels. Nuclear magnetic resonance (NMR) analysis confirms this structural evolution, showing a reduced Si/Al ratio of 1.49 and an extended mean aluminosilicate chain length of 57.70, indicative of enhanced three-dimensional network connectivity. Consequently, the 28-day compressive strength increases by 21.30% to 54.3 MPa and the elastic modulus by 26.41% to 12.11 GPa, surpassing the performance of hybrid geopolymer systems and exceeding the elastic modulus of OPC paste at equivalent strength. The core-shell structure demonstrates exceptional synergy, quantified by a synergy coefficient of 1.35, compared to 0.61 for the physical CS/NS blend. Sustainability advantages include waste valorization through CS-derived NS synthesis via exothermic acid-leaching with $\Delta H = -181$ kJ/mol, which replaces costly commercial NS, along with minimal PVP usage constituting 10% of CS mass, mild processing, and scalability. Thus, by converting industrial waste into high-value additives, this research establishes a sustainable pathway for manufacturing high-performance

geopolymers with combined structural reliability and environmental benefits, addressing application barriers in infrastructure, architecture, and industrial engineering.

Plain and steel fiber reinforced geopolymer composite resistance to different levels of dynamic load application in tension

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Keywords: Geopolymer composites, dynamic loading in tension, fatigue properties

As a novel material, geopolymer has raised interest, and thus, many publications have been written and published regarding its mechanical and long-term properties in the previous years. Nevertheless, experimental data and analysis regarding dynamic loading impact have been scarce, especially reflecting tensile stresses and geopolymer composite interaction. This article aims to evaluate the effects of the introduction of dynamic loading in tension to unreinforced and steel fiber reinforced geopolymer composites. The testing and test setup is based on ASTM E1820-01 and ASTM E647-15 testing standards. The chosen test specimen shape and techniques mimic dynamic loading that may occur on structures such as bridge span and deformation joint interaction under live transport loads or road surface plate elements under rapid and continuous transport movement. The compact tension specimens were subjected to dynamic load with different loading levels (0.5 to 0.7 of their strength values), different loading amplitudes, and frequencies. For testing purposes, Instron E3000 is used not only to exhibit dynamic loading but also to determine the tensile strength of the specimens. All of the specimens were subjected to 100,000 cycles of loading. At the early age of the loading, specimens exhibit a slight increase of the displacement (the notch area is, in a way, opening) in boundaries of 0.009mm to 0.021mm. This is for both plain and steel fiber-reinforced specimens with greater values exhibiting specimens without reinforcement. This displacement increases from the 1st cycle till the 200th cycle. Afterward, it stays still till the 800th or 2000th cycle, depending on the loading rate and specimen type. Further, displacement drops to the values from -0.017mm to -0.028mm (in reference to 0.000mm displacement at the very beginning of the test). The greatest decrease of the strain drops exhibits specimens with fiber reinforcement that have been subjected to a dynamic load base value of 0.5 of their strength value and been loaded with an amplitude of +/- 0.2 of the strength value. To further see if this characteristic is significant to only geopolymer composites or if it might be characteristic of the chosen specimen shape, the same testing was done on plain concrete specimens. Regular Portland cement-based concrete exhibits the same early displacement increase as the plain geopolymer (on average, in the first 600 cycles, displacement increases to 0.019mm), but at the end of the 100,000 cycles, dynamic test displacement drops only to -0.04mm. Furthermore, the characteristic of displacement change is different to the geopolymer composites exhibited – for concrete, it is as rapid in the early stage of the testing as for the geopolymer composites, but after 30,000 cycles, displacement starts to reduce its development rate as for the geopolymer composites it does not reduce that significantly. This shows a rather significant geopolymer composite self-tension effect as a response to dynamic load subjection. What is more interesting is that if the load level is smaller, but the amplitude of load change is greater, the displacement variation (at the beginning and end) is greater, too. The main purpose of this article is to gain insight into fiber reinforcement's ability to reduce dynamic tensile strain influence on geopolymer composite durability and verify dynamic loading influence on geopolymer composite structure.

Properties of 3D printable eco-friendly alkali-activated mortar after exposure to service conditions

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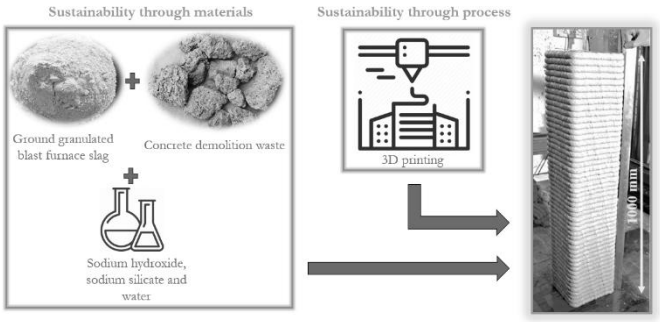
Keywords: 3D printing, alkali-activated, concrete demolition waste, column.

Low productivity is one of the challenges that the construction industry is facing today. This challenge can be overcome by automating the process of construction through extrusion-based 3D printing of concrete. It involves layer by layer deposition of fresh concrete to build the structure. The process of 3D printing includes the fresh material to be pumped through a hose and extruded through a nozzle. This requirement of pumpability and extrudability is usually met by formulating the mixtures with high binder content. The conventionally used binder i.e., ordinary Portland cement (OPC) has high embodied energy and associated greenhouse gas emissions. Hence, the use OPC in binder rich 3D printable mixtures would make the end product less sustainable. Further, natural aggregates which are the most commonly used aggregates in 3D printable mixtures are fast depleting. Therefore, in this study eco-friendly 3D printable mixtures were formulated using – (i) alternative cementitious materials such as alkali-activated materials which uses industrial residues (Ground granulated blast furnace slag) as binders and (ii) concrete demolition waste as aggregates. Further, from the mechanical strength and durability perspective of 3D printed structure, it is important to understand whether the properties of the developed mixtures vary after exposure to the service conditions. Therefore, the objective of this study is to assess the properties of an eco-friendly alkali-activated mortar-based 3D printed column after subjecting it to natural service conditions similar to that of any building in Mumbai, India.

Initially, the effect of mixture parameters such as activator dosage, molar modulus and water to binder ratio on the workability and its retention, of the mixtures was evaluated through flow table test. The selected mixtures were then assessed for pumpability, extrudability and buildability. Pumpability was assessed through successful pumping of the mixtures through a 16.5 m pumping circuit while extrudability was assessed through successful extrusion of the mixtures through a 20 mm diameter nozzle. Buildability was measured as the total height of 200 mm hollow square model that could be printed without failure. Two hollow 200 mm square column of 1 m height and 20 mm layer thickness was printed using a 20 mm circular nozzle. Both were moist cured for 28 days. 15 mm cubes were extracted from the column and tested for compressive strength and sorptivity. Further, the pore structure of the specimens was captured through 4D Xray microscopy and mercury intrusion porosimeter. TGA, XRD and FTIR were done on the powdered samples from each of the columns to evaluate any possible changes in the reaction products due to exposure to service conditions. These tests were done on one of the columns after curing (control sample), while the other column was exposed to natural conditions for a period of 6 months before testing.

The increase in activator dosage and molar modulus reduced the workability of the mixtures while the increase in water to binder ratio increased the workability of the mixtures. Mixtures with a flow table spread diameter in the range of 165-185 mm were found suitable for printing. The printable mixtures recorded a pumping pressure in the range of 9-16 bar and could be successfully extruded and printed with good print quality. The mixtures also provided an exceptional open time of 3 hours and buildable heights of 760-1000 mm. It was found that the specimens did not undergo significant changes due to exposure to service conditions. The specimens from the column after exposure exhibited refined pore structure and had carbonates phase in the composition indicating natural carbonation. This results from the study suggests that the developed eco-friendly 3D printable mortars were resilient under natural service conditions.



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Role of carbonation curing and GGBS on properties of fly-ash based geopolymer

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Keywords: carbonation curing, GGBS, Fly-ash, geopolymer

As environmental concerns continue to rise, it has become increasingly important to reduce both cement consumption and the associated CO_2 emissions. In this study, the authors investigate the effects of carbonation and the incorporation of ground granulated blast furnace slag (GGBS) on the microstructure and mechanical properties of fly ash-based geopolymer materials. The interaction between carbonation and alkali-activated systems, particularly those rich in calcium such as GGBS-blended geopolymers, remains insufficiently understood. The behaviour of carbonation in these systems is complex, with unclear implications for the microstructural development and overall performance of geopolymers. Gaining a deeper understanding of how carbonation and GGBS impacts key properties is crucial for optimizing the design and performance of geopolymer-based materials in sustainable construction applications.

Three optimized mixtures, incorporating 0%, 20%, and 30% GGBS, were prepared and subjected to accelerated carbonation under CO_2 concentrations (20% CO_2, 20°C, 60% RH) for specific periods. In addition to carbonation curing, air curing was also employed as a control method. Phenolphthalein tests were conducted on the specimens, revealing a notable reduction in pH across all samples. This pH decrease is indicative of the carbonation process, confirming the successful incorporation of CO_2 into the geopolymer matrix.

X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) were employed to investigate the carbonation products formed in the fly ash-based geopolymer specimens. These analyses identified natron, nahcolite, and calcite as the primary carbonation products. Specifically, natron and nahcolite were predominantly observed in the carbonated specimens without the inclusion of GGBS, suggesting that carbonation primarily formed these products in the absence of additional calcium sources. On the other hand, calcite formation was notably associated with the presence of GGBS, indicating that the calcium-rich nature of GGBS promotes the formation of calcite during the carbonation process. Furthermore, TGA results revealed a clear trend, as the GGBS content increased, the quantity of carbonated products also increased. This indicates that the incorporation of GGBS results in the higher availability of calcium in the matrix, which facilitates the formation of additional carbonated phases.

Shrinkage measurements revealed significant improvements in carbonated specimens, particularly in those containing GGBS. This improvement can be primarily attributed to the reduction in pH and the availability of alkali hydroxides induced by the carbonation process, which slows down the dissolution of GGBS and the subsequent formation of the geopolymeric gels. Additionally, the formation of carbonation products possibly contributes to the blockage of water-loss pathways, which limits the phenomenon of self-desiccation. The carbonation process not only helps in reducing water loss but also binds sodium and

calcium ions into carbonated products, thus it is possible to decrease ion mobility. This reduced ion mobility and water loss possibly leads to stable internal structure, with fewer volume changes.

In terms of compressive strength, specimens containing GGBS exhibited higher strength than those without. However, carbonation slightly reduced the compressive strength of the specimens, which may be attributed to the decalcification of C-(A)-S-H gel and its transformation into calcite, which aligns with the observed changes in microstructure tests. This transformation can alter the microstructure and geopolymeric gel stability.

Carbonation leads to the formation of natron, nahcolite, and calcite. Although this process results in a slight decrease in strength, it simultaneously enhances shrinkage performance, particularly in GGBS-containing mixtures, by stabilizing the internal environment and minimizing the pathways for water loss. Thus, carbonation may be appeared to offer a balance between strength loss and shrinkage reduction, with notable benefits in volumetric stability, especially when GGBS is incorporated into the geopolymer mix. Understanding these interactions is essential for optimizing geopolymer formulations for sustainable construction applications.

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Studies on ternary alkali-activated hybrid binders

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Keywords: hybrid binders, calcined clay, natural pozzolana, alkali-sulfate

The increasing demand for clinker reduction in the cement industry has raised significant interest in supplementary cementitious materials (SCMs) such as natural pozzolanas and calcined clays. However, high clinker replacement often results in slower early-age strength development, which can be a critical drawback in construction applications. To address this issue, alkali activators are introduced to enhance early hydration by increasing pH, promoting silicate dissolution, and accelerating strength gain. Despite these benefits, the complex interactions between alkalis, sulfate, and SCMs in low clinker systems remain insufficiently understood, necessitating further research.

This study investigates alkali-activated ternary hybrid binders in two systems with clinker content below 30%. The first system is based on Portland clinker, calcined clay, and limestone and the second system is based on Portland clinker, volcanic pozzolana, and limestone. Three different alkaline activators—sodium sulfate, sodium carbonate, and sodium metasilicate pentahydrate—are used at fixed alkali equivalent contents of 1.5% and 3%. Additionally, calcium sulfate is added to some of the systems for further optimization. Compressive strength is measured at 2, 7, and 28 days, while X-ray diffraction (XRD) and thermogravimetric analysis (TGA) are performed on selected hydration-stopped samples. Hydration stoppage was done through solvent exchange method.

The results demonstrate a significant improvement in early-age strength in the presence of sodium sulfate, with minimal adverse effects on 28-day strength compared to other activators. This enhancement is attributed to ettringite formation, as confirmed by XRD analysis. The addition of extra sulfate to the calcined clay-based systems showed that at the same sulfate content, the three activators exhibit similar strength enhancement at 2, 7, and 28 days. This finding is promising as it indicates that sodium sulfate, which is more environmentally friendly and easier to handle, can deliver similar performance to e.g., sodium metasilicate, which has higher CO_2 emissions. Nevertheless, in the volcanic pozzolana-based system when no activator was used, the addition of sulfate did not improve the compressive strength at 2 or 7 days. However, in the presence of an activator, additional sulfate improved the compressive strength.

TGA results indicated fast portlandite consumption, such that in both systems in presence of activator, portlandite was not detected after 7 days of hydration. This was attributed to the ultra-low clinker content used in such systems.

Finding of this study emphasize the critical role of sulfate balance in alkali-activated hybrid binders, where low clinker, alkali activation and high SCM addition significantly influence sulfate availability and hydration

kinetics. The study offers valuable insights for developing more sustainable and high-performance hybrid cementitious systems.

The impact of organic impurities on the mechanical properties of alkali-activated glass-based binders

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Keywords: Alkali-activated binders, glass powder, casein, impurity

Alkali-activated binders (AABs) using glass powder have shown promising mechanical performance under controlled laboratory conditions, for instance, studies have reported 28-day compressive strengths reaching up to 59.2 MPa when glass powder is used as a precursor in AABs.

Organic impurities, such as glue and paper labels, commonly found in recycled glass, can interfere with the alkali activation process, affecting hydration and strength development in alkali-activated binders (AABs) based on glass powder. This interference is a key aspect that has not yet been widely explored in the literature. In contrast, organic impurities, although they have a variable effect depending on the type of binder, are well studied. For instance, in lime and clay-based binders, organic impurities can increase strength due to their ability to promote the reactivity of the components. However, in cement-based binders, they may have the opposite effect, reducing strength due to air entrainment or other phenomena. This study, therefore, focuses on the impact of organic impurities on the hydration and strength of alkali-activated glass binders, which may disturb the hardening process, but whose specific effect remains to be further investigated.

In this work, a glass-based binder was developed and showed good strength results, this was done under laboratory conditions using clean glass powder. However, when scaling up to industrial applications, the glass used may not be completely clean and could contain impurities such as glue, paper labels, and other residues from recycling processes. These impurities might interfere with the alkali activation process, affecting both the hydration and final mechanical properties of the binder. To explore this issue, the effect of pure casein on the performance of the binder was investigated.

Casein is a protein-based adhesive commonly used in glass bottle labels and was selected as a representative organic impurity. Under realistic industrial conditions, casein content would be around 0.1% per bottle, however, to understand better the effect of organic impurities on the binder matrix, higher percentages were selected. Therefore the 0-5 wt% of casein were introduced into the binder formulations. Besides compressive strength testing, the hydration mechanisms of the binder were studied using isothermal calorimetry. The isothermal calorimetry measurements were performed on mixes containing 0wt%, 1wt%, 2wt%, 3wt%, 4wt%, and 5wt% casein for 14 days, whereas the compressive strength was tested on samples with 0wt%, 1wt%, and 5wt% casein at 1, 2, and 28 days to evaluate how casein affects the mechanical properties over time.

The experimental results demonstrated a clear negative impact of casein on the binder's compressive strength. As the casein content increased, both early-age and later-age compressive strength decreased significantly. For the 1% casein addition, the binder lost 15.8% of strength on day 1, 16.8% on day 2, and 21.4% on day 28 in comparison to the binder without casein. For the 5% casein addition, the binder lost 73.6%, 73.1%, and 69.1% on day 1, day 2, and day 28, respectively. Calorimetry measurements showed that the intensity of peaks becomes lower as the casein level increases, especially in the case of 3% to 5% where the reactions started around days 6-7, while with 0% impurity, it started from day 1. This means that casein blocks or delays the hydration reaction. It was also observed that the introduction of casein into the binder negatively affected its rheology, with poorer flow properties as the casein content increased. This worsening rheology could contribute to the observed decrease in compressive strength, as it leads to the formation of voids, which in turn increases porosity and reduces the binder's compressive strength.
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In conclusion, this study demonstrates that organic impurities can influence the hydration and mechanical performance of alkali-activated glass binders. The addition of 1% casein was found to slow down the hydration process and reduce both early and long-term compressive strength, although the impact was moderate. In contrast, a 5% casein addition significantly reduced mechanical performance. Furthermore, the presence of casein negatively affected the rheology, worsening it as the casein content increased.
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Understanding the Role of Temperature on the Dissolution Process of Alkali-Activated Slag: A Path to Enhanced Reactivity at Low Temperatures

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Keywords: blast furnace slag, alkali-activated slags, reactivity, dissolution, cold temperature.

Alkali-Activated Materials (AAMs), particularly Ground Granulated Blast Furnace Slag (GGBS)-based Alkali-Activated Slag (AAS), have emerged as a promising green alternative to cement-based binders due to their lower carbon footprint and satisfactory mechanical properties at ambient temperatures. With growing global emphasis on carbon neutrality and sustainable infrastructure, the deployment of low-carbon alternatives like AAS in all climate zones is becoming increasingly critical. However, the limited reactivity of AAS at low temperatures (5 to 10°C), especially in early ages, remains a major barrier to its large-scale application in colder regions. These temperature ranges, while not extreme, are very common in Europe and parts of Asia for several months of the year, making this issue particularly relevant for real-world implementation. Current solutions involve maintaining ambient temperatures on construction sites using warm sheds and electric blankets. These measures, although effective, are costly and energy-intensive, thereby negating the CO_2 reduction benefits of AAS. Recent studies have explored the possibility of remediating the low early-age strength using calcium salts or silicate-based activators with a high silicate modulus. These methods, while showing promise, often suffer from delayed setting times, and inadequate compressive strength development in the 5–10°C range. As a result, they have not yet achieved satisfactory performance at early ages under low-temperature conditions. To achieve better results, there is a need to delve deeper into the impact of low temperatures on the fundamental mechanisms of AAS hydration—specifically, the dissolution-precipitation process. A better understanding of this stage is essential for developing targeted solutions to the observed low reactivity. This study aims to investigate the role of temperature during the dissolution phase of AAS hydration, the precursor to the precipitation reaction and a key determinant of early-age strength. Dissolution experiments (employing NaOH as an alkali activator) were conducted at 5°C, 20°C, and 40°C using a high liquid-to-solid ratio (500) to suppress precipitation and isolate the dissolution behaviour. Two complementary techniques were used to monitor dissolution kinetics: pore solution conductivity measurements (over a 20-hour period) and continuous ICP-OES analysis (over 120 minutes). The latter allowed real-time quantification of key ionic species such as Si, Ca, and Al. These solution-phase observations were supported by solid residue analysis using Scanning Electron Microscopy (SEM), Thermogravimetric Analysis (TGA), and X-Ray Diffraction (XRD) to detect any secondary reaction products and unreacted phases. The results clearly show that dissolution is significantly hindered at 5°C, which likely limits subsequent hydration and strength development. However, this adverse effect can be mitigated by increasing the fineness of slag. Tests on coarse slag, fine slag (d50 = 10 μm), and ultra-fine slag (d50 = 5 μm) revealed that higher specific surface area accelerates dissolution, even under cold conditions. In contrast, coarse slag achieved effective dissolution at elevated temperatures. These findings suggest that optimizing slag fineness presents a practical and less energy-intensive route to improving AAS performance in cold environments, thus unlocking its full potential in lowering the CO_2 emissions of the construction industry. Building on these findings, ongoing research will explore alternative activation strategies to further enhance early-age AAS reactivity at low temperatures.

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Vegetable fibers as sustainable reinforcement in geopolymer matrices: study of strength, adhesion, and durability

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Keywords: Vegetable fibers, geopolymers, alkaline hydrolysis, pullout test, sustainable composites.

Given the environmental impacts associated with Portland cement production—which accounts for approximately 8% of global carbon dioxide (CO_2) emissions—geopolymeric binders have emerged as promising alternatives due to their lower environmental footprint, especially when raw materials are properly selected. However, like other ceramic-based materials, geopolymers tend to exhibit brittle fracture behavior and significant chemical and drying shrinkage, which can limit their mechanical performance in structural applications. To address these limitations, the incorporation of fiber reinforcements has been widely studied, with increasing interest in the use of natural vegetable fibers (VF) due to their renewable nature, low cost, and reduced environmental impact compared to synthetic or metallic fibers. Nonetheless, using VFs in cementitious or geopolymeric matrices presents significant challenges related to their long-term durability, as the high alkalinity of the matrix can trigger gradual degradation through alkaline hydrolysis, compromising the fiber/matrix interfacial bond and, consequently, the mechanical properties of the composite. In this context, the present study aimed to evaluate the stability and adhesion of natural and treated plant fibers embedded in geopolymeric matrices with varying levels of free alkalis, using pull-out tests as the primary methodology, complemented by tensile strength tests, thermogravimetric analyses (TGA/DTG), and microstructural characterization. Matrices with both minimum and maximum free alkali contents were prepared using sodium and potassium hydroxide activators (GNa_{min}, GNa_{max}, GK_{min}, and GK_{max}). These matrices were reinforced with untreated fibers (FR), fibers treated with sodium hydroxide solution (FNa), and fibers subjected to hornification (FH). All fiber types exhibited water absorption rates exceeding 150%, indicating that neither treatment provided impermeability or prevented the uptake of alkaline ions from the matrix pore solution. In tensile testing, only the FNa fibers embedded in GNa_{min} and GK_{min} matrices maintained strength values statistically comparable to untreated fibers, while fibers in matrices with maximized alkali content (GNa_{max} and GK_{max}) experienced significant degradation, especially the hornified fibers, which were completely compromised by alkaline hydrolysis. Pull-out tests showed a reduction in fiber/matrix adhesion between 3 and 28 days in all sodium-based matrices, suggesting progressive degradation of amorphous fiber components such as lignin and hemicellulose. In GNa_{max} matrices, fiber rupture occurred after 28 days at lower loads than initial pull-out forces, indicating structural deterioration. The best adhesion performance was observed in FNa fibers embedded in GNa_{min}, corroborating tensile results and confirming that alkaline treatment removes easily degradable compounds and preserves interfacial integrity. Fibers in the GK_{min} matrix maintained stable adhesion and friction stress values after 28 days, indicating effective mechanical anchorage and enhanced composite toughness. Thermogravimetric analyses showed that fibers from high-alkali matrices decomposed at lower temperatures, suggesting structural changes and weakened molecular bonds. Microstructural observations revealed mineral deposits on the fiber surface and in cracks, along with cellulose fibril disintegration in a helical pattern, particularly in hornified fibers, indicating advanced hydrolysis. It is concluded that the geopolymer matrix composition plays a critical role in the durability of natural fibers. In highly alkaline matrices, none of the treatments ensured fiber integrity, consistent with findings in Portland cement matrices. The most favorable condition was the combination of alkaline-treated fibers and geopolymer matrix with lower alkali content (sodium-based), which provided superior interfacial stability and

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Volume 1

Section 1.4: Traditional and New Cementitious Materials

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A Model-Based Evaluation of CO_2 Emission Reduction and Energy Efficiency Measures in Cement Plant Operations Towards Net-Zero Emissions

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Keywords: Assessment model, Cement plants decarbonization, 5Cs decarbonization approach, CO_2 reduction measures, Cement industry.

The cement industry is one of the most energy and carbon intensive sectors, responsible for approximately 8% of global CO_2 emissions. With rising infrastructure and urbanization, achieving net-zero emissions (NZE) in cement production is critical to global climate goals. Despite the development of several technologies, strategies, and decarbonization pathways, such as carbon capture, LC^3 cements, renewable energy integration, and alternative fuels and raw materials, the industry lacks a comprehensive and structured approach aligned with the 2050 NZE and plant-level goals to systematically evaluate, prioritize, and rate various CO_2 emissions reduction and energy efficiency improvement measures. The challenge lies in the absence of an accessible, data-driven, scalable, and adaptable tool to evaluate the effectiveness of these measures. This study addresses that gap by introducing a tailored, data-driven, model-based, assessment and decision-support tool specifically for cement industry. It assesses decarbonization performance through a structured set of CO_2 improvement measures across the cement value chain using an Excel-based assessment-tool to reach NZE. The tool supports strategies evaluation, scenarios planning, and CO_2 reduction monitoring aligned with global benchmarks and plant-level targets.

The model is built on a set of key decarbonization measures, strategies, computations, and best practices in cement production categorized into five main areas which are process and technology efficiency, alternative fuels and energy management, alternative raw materials and clinker production, process emission control and industry innovations, and facility operations and optimization. It integrates a multi-criteria framework based on cement plants energy and materials input-output model. For that, the cleaner production theory and the 5Cs approach for cement decarbonization by 2050 focusing on clinker, cement, concrete, construction re(carbonation), and carbon capture and storage (CCS/CCU) are used in identifying and categorizing the CO_2 improvement measures by acting at different stages of the value chain achieving a systematic yet flexible method of evaluation. These measures are assessed across their implementation level, CO_2 emission reduction, significance rate, environmental impact, and operational integration. A total of 14 1st level and 43 2nd level subareas improvement measures are evaluated by the tool. Each measure is scored using a combination of qualitative expert input, surveys, and quantitative sustainability reports, computed metrics, and actual on-site real-time monitoring data. These computed scores contribute to an overall plant's sustainability performance score, visualized using graphs, radar chart for historical evaluation, and a color-coded system on a scale from 1 to 5, with 1 representing the least implemented measures. The tool is designed to be user-friendly, replicable, and adaptable across different regulatory, geographic, and operational contexts. Built on the hierarchy assessment model, it enables benchmarking and comparisons across different plants, offering valuable insights, compliance verification, and resources allocation, surpassing the scope and flexibility of the existing sustainability platforms.

To validate the tool's applicability, a case study was conducted on cement plant A, a major cement plant and a global key player in the cement industry based in Egypt. The tool evaluated both real operational data and company-reported sustainability measures. Plant A achieved an overall sustainability score of 3.441 out

of 5, indicating a high on-track implementation level of the proposed CO_2 improvement measures. Notably, the plant had strong integration of waste heat recovery systems, real-time energy monitoring, application of energy efficiency technologies, the use of alternative raw materials and fuels, and facility operations. The results highlight that targeted operational improvement, especially in thermal efficiency and process monitoring yield the most significant impacts on emission reduction, while low scoring in renewable energy integration and carbon capture techniques highlight areas for future improvement.

In conclusion, the proposed assessment model provides a practical and robust tool for evaluating cement plants' performance in line with global climate goals, milestones, and plant-level targets. Its application facilitates informed decision-making, strategic resource allocation and investments, prioritization of high-impact actions and computed scores, and enables continuous improvements. Beyond the Egyptian case, the model is adaptable to other geographical regions, bridging the gap between global NZE targets and plant-level sustainability goals. By facilitating measurable assessment, the model contributes to accelerating the decarbonization of one of the most critical carbon-intensive industries.

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A Novel Segmentation Approach for Micro-CT Analysis of Lightweight Aggregate Concrete

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Keywords: Lightweight aggregate concrete, Micro-CT imaging, Segmentation, Pore structure characterization, Durability

Lightweight aggregate (LWAC) is widely used due to its low density, thermal insulation, and fire resistance. However, these advantages are generally achieved through the incorporation of highly porous lightweight aggregate that increases permeability and reduces strength compared to conventional concrete. Therefore, a detailed analysis of the pore structure of LWAC is necessary to improve the durability, thermal, and mechanical properties of LWAC. Among several material characterization techniques, recent advances in micro-computed tomography (micro-CT) imaging allow non-destructive visualization of internal pore structures at high resolution. By utilizing grayscale micro-CT images, it is possible to differentiate pore structures from solid regions, allowing for accurate characterization of pore size, shape, and distribution. However, the accuracy of these analyses heavily relies on the segmentation process, which determines how effectively pores, aggregates and cement paste are classified. Thus, proper segmentation is a crucial step in image processing, and conventional methods include histogram-based approaches, probability distribution methods, and morphological techniques.

In micro-CT images of LWAC, accurate segmentation of solid phases, aggregates, and pores is crucial, as pore connectivity is directly related to durability, strength, and other properties. Among them, durability is a fundamental property that determines the long-term performance and structural stability of concrete. Maintaining high durability is particularly critical for concrete exposed to harsh environmental conditions, such as moisture, chemical exposure and freeze-thaw cycles. However, durability is significantly influenced by pore connectivity and permeability, which affect the penetration of water, chemicals, and chlorides. As a result, accurate characterization of internal pore structures is essential for evaluating concrete durability, particularly in highly porous materials such as lightweight aggregate concrete.
LWAC presents significant segmentation challenges due to the highly porous nature of lightweight aggregates, which complicates the differentiation between aggregates, intra-aggregate pores, and cement paste pores. Unlike conventional concrete with normal aggregates, where segmentation focuses primarily on classifying pore spaces and solid phases, lightweight aggregate segmentation must account for variations in aggregate density and surface irregularities, which frequently lead to over-segmentation and misclassification errors. One of the key challenges results from the varying durability of lightweight aggregates depending on particle size, which can result in misclassification of aggregates as pores. In addition, irregular aggregate surfaces introduce segmentation inconsistencies, affecting pore structure characterization and decreasing the reliability of numerical simulations based on these models. Such errors can lead to incorrect permeability and thermal conductivity predictions, ultimately impacting durability assessment and structural design applications of the materials.

To address these challenges, this study proposes an advanced segmentation algorithm for precise LWAC micro-CT image analysis. Unlike conventional segmentation methods that primarily rely on histogram-based statistical approaches, the proposed algorithm enhances accuracy by integrating morphological techniques that leverage shape information. The developed algorithm contains morphological operations, including dilation, and applies the H-Maxima method, which filters out non-essential features while preserving significant contrast regions. In addition, erosion followed by dilation is applied to enhance aggregate boundaries, while the watershed algorithm effectively separates connected aggregates. The algorithm also incorporates variations in aggregate density to improve differentiation between aggregates, pores, and intra-aggregate voids. To validate the effectiveness of the proposed algorithm, specimens with a known number of lightweight aggregates were produced, and corresponding CT images were acquired. Comparative analysis between the proposed and conventional segmentation methods demonstrated that the newly proposed algorithm significantly improved aggregate segmentation with minimized misclassification errors. Furthermore, numerical simulation using 3D micro-CT image data were conducted to investigate the differences of permeability and thermal conductivity according to different segmentation methods. The obtained results demonstrated notable differences in the simulation outcomes, further emphasizing the importance of accurate segmentation for predicting long-term performance of LWAC.

The findings of this study highlight the crucial role of advanced segmentation techniques in enhancing the reliability of micro-CT image-based pore analysis. By improving pore and aggregate segregation, the proposed algorithm contributes to more precise numerical modelling, better durability assessments, and improved predictive performance in structural applications. These findings underscore the necessity of accurate pore structure characterization for sustainable concrete design and performance evaluation.

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Additives to Improve the Performance of Carbonate-activated Slag Cements

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Keywords: Alkali-activated cement (AAC), in situ, reaction mechanisms

Alkali-activated cements (AACs) are a promising alternative to traditional Portland cement (PC), having the potential to reduce cement-associated carbon emissions by up to ~80% through their use of industrial waste and/or by-products, as well as naturally occurring minerals. Despite this, commonly used 'activators', alkali hydroxides and silicates, possess a greater embodied carbon than their less widely used counterparts, alkali carbonates, which are naturally occurring or can be produced via carbon sequestration. Limited use of alkali carbonates in the production of AACs is attributed to their lengthy initial setting and hardening time, and poor early strength development.

This study aims to understand the reaction mechanisms and kinetics of alkali carbonate-activated slag binders to provide new insight to explain physical property development. Furthermore, the effect of additives to improve the performance of the carbonate-activated binders is also explored. This will enable optimisation of formulations for enhanced performance, and thus, drive rapid industrial implementation.

Cement paste samples were made using blast furnace slag (BFS) (Ecocem, Dunkirk) and sodium carbonate solution at a set dosage and water-to-solids ratio, mixing for 10 minutes with a high-shear mixer, then promptly transferred to the respective analysis equipment. The initial formulation was designed to be consistent with previous studies on reaction, microstructure and nanostructure of AACs using carbonate-based activators. Further samples, incorporating calcium oxide (CaO) as an additive to improve performance, were made in the same way, with the additive replacing small amounts of BFS. The samples are detailed in Table 1.

Table 1. Chemical formulations of alkali-activated slag pastes.

	Sample Name	BFS (g)	Activator Na_2O (g)	CaO mass (g)
A	BFS_Na_2CO_3	100	8	0
B	BFS_Na_2CO_3_1%_CaO	99	8	1
C	BFS_Na_2CO_3_3%_CaO	97	8	3

Isothermal conduction calorimetry (ICC) was conducted at a constant temperature of 20°C to study the reaction process of cement pastes over a period of 75 hours. The initial reaction was further probed through the use of diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS) to assess changes in bond environments *in situ*, and X-ray diffraction (XRD) to identify the crystalline phases present. Spectra measurements and XRD patterns were taken every 2 and 15 minutes after mixing, respectively, for the first few hours to explore the reaction mechanisms

Data from ICC, DRIFTS and XRD evidence that a preferential reaction is occurring in the initial few hours for the sodium carbonate-activated slag binder, causing the characteristic slower setting time associated with carbonate-activated binders. These observations suggest that the calcium ions from the slag are preferentially reacting with the carbonate anions of the activator to form calcium carbonate and sodium calcium carbonate polymorphs. These carbonate phases, as well as the slower dissolution of BFS under moderate pH from the activator, retard the reaction, causing the longer induction period. However, once the carbonate ions are exhausted, the activating reaction is expected to continue similarly to sodium hydroxide-activated slag binders.

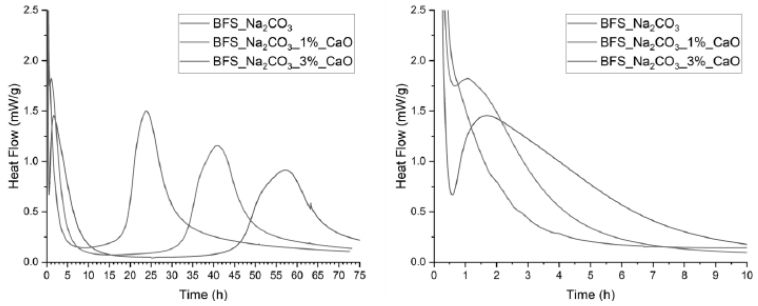

Figure 1. Heat release rate of sodium carbonate-activated slag with and without calcium oxide, over the first 75 hours (left) and 10 hours (right).

Calcium oxide was incorporated in the sample matrix with the aim to increase the overall reaction, giving a more comparable reaction time achieved by the likes of silicate- and hydroxide-activated binders. Calorimetry data (Figure 1) reveals that the inclusion of CaO, even in small amounts (1 and 3%), speeds up the reaction, with the acceleration periods for samples B and C occurring ~15 and ~30 hours sooner, respectively, than that of sample A. It is also evident that the initial preferential reaction previously observed is greatly reduced in sample B and completely superseded in C.

DRIFTS data for samples including 3% calcium oxide confirm that no preferential reaction is occurring, and that instead, the increased calcium in the system is facilitating calcium supersaturation in solution to allow the main reaction to proceed, specifically the precipitation of C-(A)-S-H – the main strength-giving phase of AACs. As such, the incorporation of calcium oxide improves the reaction and performance of carbonate-activated slag cements and thus has the potential to improve the industrial application capability of the material.

Further analysis of these samples, particularly solid-state testing methods, including electron microscopy (SEM-EDX), 27Al and 29Si MAS NMR, and compressive strength testing provide insight into the physical performance of the samples beyond the initial reaction and setting. Altogether, the understanding of the fundamental chemistry governing the physical property performance will aid in the optimisation of formulations for use in industry.

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A physical properties on Bentonite clay for sustainable construction materials

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Keywords: Bentonite, compaction, sintering, thermal conductivity, mechanical strength

Bentonite is a versatile clay material widely used in construction, thermal insulation, and geotechnical applications due to its unique properties. However, its swelling nature and sensitivity to water hinder its direct application without treatment. This study investigates the physical properties of Moroccan bentonite under different compaction intensities, water contents, and sintering temperatures. The research aims to provide a comprehensive understanding of the influence of these factors on the material's mechanical, thermal, and electrical behavior, thus contributing to the optimization of bentonite-based composites for sustainable construction applications. Bentonite samples were prepared in three thermal states: (a) immediately after sample preparation (ASP), (b) after curing for 28 days followed by drying at 105°C, and (c) after sintering at temperatures between 700°C and 1000°C for 6 hours. The material was characterized using various experimental techniques: X-ray fluorescence (XRF) to determine the chemical composition of the bentonite, X-ray diffraction (XRD) and scanning electron microscopy (SEM) to analyze the microstructure and mineralogical composition, thermogravimetric analysis (TGA) and differential thermal analysis (DTA) to study thermal stability and water loss behavior, complex impedance spectroscopy (CIS) to evaluate electrical conductivity and permittivity, Hot Disk transient measurement method to measure thermal conductivity and specific heat capacity, and mechanical testing to determine compressive strength and Young's modulus under different compaction intensities. The compaction intensities varied from 14 MPa to 210 MPa. Water content ranged from 0% to 20%. The effects of compaction, water content, and sintering were systematically analyzed. Increasing compaction intensity led to a higher apparent density due to volume reduction, while mass remained nearly constant. Thermal conductivity (λ) and maximum compressive strength (Rcmax) increased with compaction intensity. Electrical conductivity (σ) decreased as samples transitioned from the ASP state to dried and sintered states, correlating with the removal of free and bound water. The dielectric permittivity (ε) followed a similar trend, decreasing with higher compaction levels. Sintering between 700°C and 1000°C caused a significant increase in apparent density, reaching up to 2.28 g/cm³ at 1000°C. Thermal conductivity increased with sintering temperature due to structural densification. However, electrical conductivity showed a decreasing trend as sintering removed conductive ions and reduced porosity. Permittivity also declined, indicating reduced polarization effects. The samples sintered at 1000°C exhibited the highest mechanical strength and the lowest moisture sensitivity, making them suitable for applications requiring high durability. Water content influenced all measured properties. In the ASP state, electrical conductivity and permittivity increased with water content due to enhanced ionic mobility. Upon drying at 105°C, electrical properties stabilized at lower values. Thermal conductivity increased with water content up to 15%, after which it plateaued. Sintered samples showed lower thermal conductivity than dried samples for water contents below 15%, but higher values above this threshold. This study demonstrated that compaction intensity, water content, and sintering temperature significantly impact the physical properties of Moroccan bentonite. Increasing compaction enhances density, thermal conductivity, and mechanical strength. Sintering reduces electrical conductivity and permittivity while improving mechanical resistance. Water content plays a crucial role in electrical and thermal properties, particularly in the ASP state. The findings highlight the potential of optimizing these parameters to develop durable and sustainable bentonite-based construction materials.

Accelerated Carbonation of Ladle Furnace Slag: CO_2 Sequestration and Its Potential as a Supplementary Cementitious Material

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Keywords: Carbonation, Ladle furnace slag, CO2 capture, Valorization, mechanical properties.

Steel slag is a byproduct of steel manufacturing, with varying chemical and mineralogical compositions depending on the steelmaking process, raw materials, and refining conditions. While most steel slags exhibit low reactivity and poor volume stability—limiting their direct application in cementitious systems—some variants, such as ladle furnace slag (LFS), show potential for valorization as supplementary cementitious materials (SCMs) [1]. The feasibility of utilizing LFS in construction materials is primarily dictated by its mineral phase composition, structure, and post-processing treatments.

Global production of LFS has been increasing due to advancements in steel quality and refining technologies. In 2016, approximately 2 million tons of ladle slag were generated worldwide [2] Russia produced around 1.4 million tons in 2017 [3], while the Middle East Gulf region reported an annual output of 0.48 million tons in 2018 (Emirates Steel; Qatar Steel). Despite this substantial production volume, nearly 80% of LFS is disposed of in landfills due to its limited hydraulic reactivity and stability issues.

Recent research has highlighted the potential of accelerated carbonation as a means to enhance the reactivity and stability of LFS This process induces mineralogical transformations, alters porosity, and improves surface reactivity, thereby increasing its applicability in construction materials [4], [5]. Experimental studies have demonstrated that LFS exhibits notable carbonation reactivity, with CO_2 sequestration reaching up to 9.6% of its own mass. Furthermore, carbonation significantly mitigates environmental concerns by reducing heavy metal leaching. Specifically, Pb and Zn concentrations decrease from 2760 and 1460 μg/L to 0.11 and 0.56 μg/L, respectively—values that are well below inert waste and drinking water regulatory thresholds. In addition to these environmental benefits, carbonation markedly enhances the mechanical properties of LFS. The formation of calcium carbonate, nesquehonite, and hydromagnesite within the LFS matrix contributes to pore refinement and improved particle cohesion, further reinforcing its mechanical stability. By fostering the formation of stable carbonate phases, carbonation effectively reduces the presence of free CaO and MgO—compounds known to induce expansion-related durability concerns—thereby improving the suitability of LFS for cementitious applications [5]. However, while these findings demonstrate promising short-term enhancements, the long-term performance and reactivity of carbonated LFS within cementitious systems remain inadequately explored, necessitating further research to ensure its viability for large-scale implementation.

This study aims to investigate the carbonation kinetics of LFS under controlled conditions and assess its influence on cement hydration, mechanical properties, and durability. By elucidating the physicochemical modifications induced by carbonation, this research seeks to establish the feasibility of integrating carbonated LFS into sustainable construction materials, contributing to resource efficiency and carbon capture and utilization (CCU) strategies.

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Bio-inspired layered structural design for enhanced toughness in cement-based composites

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Keywords: Cement; Biomimetic composite; Toughening; Structure design.

Cement-based materials, serving as the cornerstone of the global construction industry with an annual production exceeding 4 billion tons, are plagued by inherent brittleness and microstructural defects that compromise crack resistance. Approximately 30% of infrastructure requires premature repair or reconstruction due to cracking. Conventional toughening techniques, such as steel fiber reinforcement (global annual consumption >6 million tons), face critical limitations:
Performance Trade-offs: Steel fiber dosages exceeding 2% reduce compressive strength by 15-30% and impair workability. Energy-Intensive Processes: The ice template method requires liquid nitrogen freezing to construct a porous structure, and the energy consumption exceeds 200 kWh/m^3. The pelletizing-hot pressing process sinters the preform at a high temperature, and the power consumption per ton of product exceeds 100 kWh.

In contrast, the strengthening and toughening strategy of natural biomaterials evolved over hundreds of millions of years has great enlightenment : the nacre has a “brick-and-mortar” structure of “brittle aragonite+trace organic matter”, which makes the fracture toughness exceed the performance limit of a single component. Bamboo achieves a perfect balance between specific strength and impact resistance by means of gradient pore and fiber orientation design. This study proposes a "natural inspiration-artificial reconstruction" synergistic strategy: ordinary Portland cement was used as the matrix, and hydroxymethyl cellulose (HPMC) was introduced as the bionic organic phase to develop a low-energy cumulative rolling process. The process simulates the self-assembly mechanism of nacre layer. By rolling cement-HPMC-water slurry layer by layer and spraying PVA between layers, the alternating structure of “hard cement layer-flexible polymer interface” (layer thickness 20~200 μm) was constructed, which does not require high temperature/freezing environment. The energy consumption is less than 5 kWh/ton, which is 95 % lower than that of traditional hot pressing method. The experimental results show that the flexural strength of the three-level structure sample reaches 52.3 MPa (515 % higher than that of pure cement), and the triple breakthrough of “strength-toughness-sustainability” is realized.

This study is expected to realize the large-scale compatibility of bionic structure design and cement-based materials, and promote three major technological innovations :

1. Intelligent construction revolution : high strength and toughness composite materials adapt to 3D printing process, solve the problem of interlayer peeling of long-span arch bridges and curved domes, and promote the integrated forming of complex structures.

2. Ultra-durable infrastructure : for pile foundations of sea-crossing bridges and buildings in high-intensity seismic zones, it is expected to extend the service life of concrete by more than 50 %.

3. Military Protective Facilities: A nacre-inspired "hard-soft" alternating layer design achieves progressive attenuation of stress waves, effectively resisting impacts from artillery shell fragments and ballistic projectiles..

This research marks a paradigm shift from “passive enhancement” to “active bionic design” in cementitious materials, providing an industrializable solution for sustainable, high-performance civil engineering materials and accelerating the construction industry’s transition toward low-carbon, high-toughness, and intelligent systems.

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Advancing calcined clay cements: development and performance evaluation

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Abstract:

Calcined clay cements (CCC) have gained significant research attention over the past five years, as calcined clay has proven to be a valuable supplementary cementitious material. However, a gap remains between research advancements and industrial cement production, as calcined clay-containing cements are only available in certain markets. This article presents the recent developments of three limestone calcined clay cements in the Benelux, incorporating 10%, 20%, and 30% of calcined clay in their compositions. The study focuses on clay characterization, calcination process optimization, and some key aspects of industrial cement production. Furthermore, the fresh-state behaviour, mechanical properties, and durability of these cements in concrete are thoroughly evaluated and compared with a range of well-established cement types. The results demonstrate that calcined clay cements can play a crucial role in reducing CO_2 emissions, addressing shifts in cement raw material availability, and maintaining high performance, making CCC a promising solution for the future of sustainable cement production.

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Analcime Sand: A Novel Additive for Low-Carbon Cement Systems

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Keywords: Waste Valorisation, Low-Carbon Cements, Sustainability, Circular Economy, Resource Efficiency

Theme: Waste recovery, treatments and valorisations; Green products

The substantial carbon footprint of the cement industry, emitting approximately 0.91 kg CO_2 per kilogram of Portland cement and contributing to nearly 8% of global CO_2 emissions, necessitates a rapid shift towards sustainable practices. Further, as the demand for infrastructure and urbanisation surges, the construction industry faces an urgent need to transition toward low-carbon alternatives such as supplementary cementitious materials, carbon capture technologies, and innovative clinker replacements. In the recent years, the cement industry has noticed a widespread adoption of supplementary cementitious materials (SCMs) like fly ash (FA) and ground granulated blast furnace slag (GGBFS), allowing reduced carbon emissions. These industrial by-products, derived from coal-fired power plants and steel production, respectively, enhance cement properties and contribute to a lower carbon footprint. However, a significant challenge for the global cement industry (especially in the UK and Europe) is the limited domestic availability of these traditional SCMs in many countries. Hence, this scarcity demands the exploration of alternative and locally sourced resources to ensure a sustainable and resilient supply chain.

Recognising this critical global need for alternative SCMs, the current work explored the potential of analcime sand, a by-product of lithium hydroxide production from Green Lithium Refining Ltd. (UK-based), as a novel valuable additive for cement and concrete for applications in the construction industry and other sectors. Lithium hydroxide is a key component of electric vehicles (EV) and static storage battery systems, with European demand rising 5-fold to 700ktpa between now and 2030. Utilising this by-product not only aligns with the principles of a circular economy but also offers a strategic advantage by leveraging a material linked to a key growth sector. Furthermore, the domestic production of analcime sand would significantly benefit the British cement industry and economy. By reducing reliance on imported SCMs, the cement industry can enhance its self-sufficiency, minimize transportation emissions, and contribute to regional economic development. The successful integration of analcime sand into low-carbon cement formulations would represent a significant step towards achieving a more sustainable and environmentally responsible construction sector in the UK, with potential for worldwide adoption. Although analcime sand shows potential to reduce clinker usage and CO_2 emissions, its application is limited by insufficient exploration into its physical and chemical characteristics along with its reactivity.

Hence, this study thoroughly investigates the physical and chemical characteristics of analcime sand to determine its potential as a novel cement additive or SCM. A comprehensive suite of analytical techniques, including X-ray fluorescence (XRF), particle size distribution (PSD), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), thermogravimetric analysis (TGA), scanning electron microscopy (SEM) were employed to elucidate the physical and chemical properties of analcime sand. Further, reactivity of analcime sand was assessed by rapid, relevant and reliable (R^3) tests using isothermal calorimetry. The results demonstrated analcime sand's suitability for incorporation into cementitious systems, as it exhibits low pozzolanic activity and advantageous physical characteristics that aid particle packing, low porosity, and substantial compressive strength. Further, the results revealed various similarities of analcime sand in terms of particle size, particle morphology and chemical composition to established supplementary cementitious materials (SCMs). These findings hold significant implications for advancing sustainable innovation, circular economy, and resource efficiency within the construction sector. Moreover, the potential applications extend beyond construction, creating new avenues for sustainable practices across diverse industries.

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Apparent activation energy of belite hydration determined through a novel (*quasi*) *in situ* X-ray diffraction method

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Keywords: Activation energy, Belite, C-S-H, *In situ* XRD, Reaction kinetics

Belite (Ca_2SiO_4 or β-C_2S) is commonly known as a minor constituent in traditional Portland cement (PC) but has recently gained renewed attention for its potential role in developing more sustainable binders as alternatives to PC. Belite-rich cement (BC) consists of belite as the main reactive component and its production is less resource-intensive, as belite offers reduced limestone demand, lower enthalpy of formation, and decreased kiln operation temperatures compared to alite, the main constituent of traditional PC. However, the comparatively slow reactivity of belite remains a significant barrier to the widespread adoption of BC.

To address this challenge, strategies have been developed to accelerate belite reactivity which include increasing the curing temperature and the addition of activators. The former exploits the strong temperature-dependence of the hydration reaction, while the latter induces a change in the rate-limiting step. Regardless of the method used, understanding the kinetics and activation energy of belite hydration is crucial for identifying the rate-limiting process and predicting the effectiveness of various acceleration strategies.

This study introduces a novel method for experimentally determining the apparent activation energy (AAE) of hydration using time-resolved (*in situ*) X-ray diffraction (XRD), with belite hydration as the focal case study. While a calorimetry-based method for measuring the AAE of hydration exists, an XRD-based technique provides the added benefit of phase-specific resolution. The method is based on previous works regarding *in situ* XRD and extends the method to slow reactions such as belite hydration, at the expense of reduced temporal resolution, hence the label *quasi in situ*. Hydration temperatures up to 80°C are accommodated, as a necessity to determine the activation energy, which requires specific procedures targeted at preventing samples from drying out, which are presented and discussed.

The case study confirms the accelerating effect of temperature on the reaction rate of belite and suggests that the induction period is also shortened with increasing temperature, although a finer temporal resolution is needed to confirm this observation. The kinetic rate constants at five temperatures ranging from room temperature to 80° C are calculated and fit to the Arrhenius equation to obtain the AAE. The AAE is calculated using the presently developed method to be around 50 kJ/mol, which shows good agreement with previously published results based on the calorimetric method and kinetic Monte Carlo simulations.

Beyond activation energy, the results indicate when specific phase dissolution and precipitation events occur at different temperatures of hydration, thus contributing to a more comprehensive perspective on the belite hydration reaction and strategies for accelerating its kinetics. Furthermore, a structural and morphological analysis of the hydrated samples shows that, while the *quasi in situ* XRD method is suitable to detect belite dissolution, it is not very sensitive to the initial precipitation of C-S-H. The C-S-H that forms upon hydration is strongly affected by the increase in temperature, showing advanced maturity and elongated C-S-H growths at higher temperature, even at a lower degree of belite reaction.

Although currently developed for belite reactivity, the method has a broad potential for application, as it can be leveraged to study the activation energy for hydration of other cementitious phases as well as of different types of reactions, such as carbonation. This innovative method can therefore become a powerful new tool in the search for effective strategies towards accelerating the reactivity of belite cements, while also being generally applicable in the search for new, sustainable alternatives to PC.

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Applying X-Ray Computed Tomography (XCT) to investigate fibre reinforced 3D printed concrete (FR3DPC)

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Keywords: Tomography, Fibres, Wind Turbine Blades, Porosity.

Evolution of 3D printed technology has recently emerged within the construction sector. The corresponding prospect of eliminating formworks and thus reducing labour activities, work completion time and environmental impact has motivated the research community to intensify relevant studies to mitigate challenges associated with the material performance. It is worth noting that most studies report that printed concrete components are often less competitive than traditionally manufactured components. The role of microstructure on the material performance has been extensively highlighted. Thus, it is essential to investigate microstructure behaviour of FR3DPC components. Beyond -traditionally employed- steel and PVC fibres used for concrete reinforcement, our study will also explore the potential of valorising end-of life wind turbine blades (EoL-WTB). Current handling of WTB waste (WTBW) management mostly involves landfilling, a practice which is not compatible with modern needs to comply with circular economy principles. Thus, repurposing the relevant waste into construction materials could offer substantial help to mitigate the environmental consequences of landfilling. We have printed four different fibre reinforced concrete layers using a bespoke-designed, and in-house manufactured vibration-based printer. Steel, PVC and WTBW fibres were used separately for each mix design to evaluate the composite behaviour and performance. The mix designs implemented were meticulously derived to perform equivalent systems and thus allow comparison. Two different WTBW size ranges were used for encapsulation, one in the range of 500um-2 mm and the other 2-8 mm. One representative 40 mm^3 cubic sample was extruded from each layer and was subsequently subjected to X-ray imaging. XCT offers a unique opportunity to "see inside the box" and, therefore, bridge the gap in corresponding knowledge. The acquired tomograms were reconstructed and used to perform 3D visualisation and phase segmentation analysis. Porosity structure was thoroughly investigated and differences between the fabricated specimens were evaluated. It is commonly accepted that porosity plays a crucial role in the material strength and durability. Not only the total pore volume but also the shape as well as the size and spatial distribution can affect the material behaviour. Therefore, a comprehensive analysis will be performed on the acquired XCT datasets to quantify all the various parameters dominating the porosity behaviour within the four different printed systems. Potential presence of fibrous elements present within the inspected volumes will be also segmented and the corresponding volumes will be illustrated separately and quantified accordingly. Fibre orientation angles will be also derived. Post imaging, the four samples will be subjected to ex-situ monotonic uniaxial loading. The compressive strength values will be correlated with the corresponding porosity and fibre orientation data to reveal potential trends. Initially printed elements will be also subjected to compressive and flexural testing, enabling comparison in the macro-scale between the different types of fibres utilised for reinforcement.

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Bridging the Interfacial Gap: Enhancing Aerogel-Cement Interfaces through Surface Modification and 4D XCT Analysis

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Keywords: Aerogel, Digital volume correlation, Coating, Lightweight concrete, X-ray computed tomography

Silica aerogels are highly promising lightweight aggregates for thermally insulating mortars and concretes, due to their exceptional thermal insulation capabilities and high-temperature stability — two characteristics that make them particularly attractive for developing lightweight, insulating concretes and mortars and improving fire safety in the built environment. However, integrating aerogels into cementitious systems poses significant challenges, primarily due to their superhydrophobic surface and mechanically fragile structure. These surface properties hinder proper adhesion to the cement matrix, leading to the formation of interfacial gaps at the interfacial transition zone (ITZ). The ITZ is already recognized as a mechanical weak spot in conventional concrete, however, the presence of interfacial gaps further compromises structural integrity and mechanical performance.

This study addresses these challenges through a targeted, solvent-free surface modification of silica aerogel granules. The goal is to transform the outer surface from superhydrophobic to hydrophilic, while maintaining the internal pore structure in its original hydrophobic state. This dual-functionality combines the benefits of both wetting states: enhanced adhesion to the cementitious matrix at the hydrophilic surface, and sustained resistance to water infiltration within the hydrophobic aerogel core. The change in wettability is confirmed through both optical goniometry (Figure 1a–b) and tensiometry, showing a significant reduction in water contact angle and improved surface compatibility with water-based binders. The modified aerogels are incorporated into a high-performance cementitious mix based on CEM I and blast furnace slag, aiming for a target dry density of approximately 1100 kg/m³ and a 28-day compressive strength of at least 10 MPa for the unmodified reference.

A suite of conventional characterization techniques is employed to assess the impact of surface treatment on both fresh and hardened properties, including mini slump flow for workability, water sorption behavior, thermal conductivity, and ultrasound pulse velocity for setting behavior. The microstructural interface is examined in two dimensions using scanning electron microscopy (SEM), while three-dimensional x-ray computed tomography (3D XCT) provides non-destructive visualization of aerogel granule distribution, particle size variation, and potential segregation. To gain deeper insights into mechanical failure mechanisms and aerogel-cement interactions under load, in-situ four-dimensional XCT (4D XCT) is conducted in a discontinuous mode, capturing the evolution of internal structure during compressive loading (up to 5 kN on 2 × 2 × 2 cm³ cubes). Digital Volume Correlation (DVC) is used to quantify internal strain fields and to monitor the initiation and propagation of cracks in relation to the properties, location, and surface treatment of individual aerogel granules (Figure 1c).

The results demonstrate that surface modification can enhance the specific compressive strength by 10 to 35%. However, this gain is accompanied by trade-offs such as decreased flowability and particle fracture during mixing, which may expose fresh hydrophobic surfaces and partially negate the intended benefits. This raises a critical question. That is, can promoting adhesion to fragile aerogel particles yield reliable mechanical improvements, or does their inherent brittleness impose a fundamental limitation?

Ultimately, this study highlights the potential of surface-modified aerogels in advancing high-performance thermally insulating concretes. Furthermore, it showcases the value of XCT and DVC as suitable tools for optimizing mix design and understanding failure mechanisms. These findings may also

have broader implications for other construction materials where the hydrophobicity makes proper integration challenging such as plasters, paints, and latex-based insulation systems.

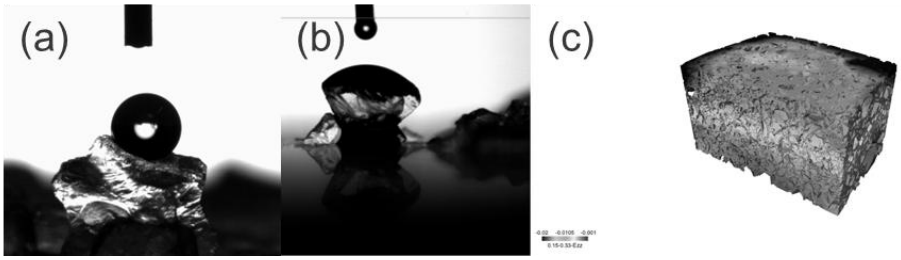

Figure 8 (a) Water droplet deposited on a hydrophobic silica aerogel particle, (b) water droplet on modified, hydrophilic aerogel and (c) strain mapping on an aerogel concrete cube using 4D XCT.

Characterization and Valorization of Phosphate Washing Sludge

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Abstract

Phosphate washing sludges are very fine particles generated during the enrichment process of phosphate. Phosphorus is separated from gangue minerals through a combination of different treatment steps: crushing, screening, washing, and then flotation. It is during the penultimate operation that phosphate sludges are formed. These sludges have a basic pH and accumulate in dikes, posing environmental issues. The idea is to valorize them by mixing with clay, fly ash, or other acidic pH mining wastes, such as those from pyrrhotite production, which are also stored outdoors. On one hand, this approach is proposed; on the other hand, there is another proposal focused on valorizing the P2O5 content in these sludges.

Currently, there are not many methods for treating these sludges. There are some applications in the building or road construction sectors, but they do not manage to consume the entire amount of washing sludge produced. Therefore, our work focuses on a new approach to valorizing these sludges, based on their geochemical composition. To this end, we have initiated a series of geochemical analyses.

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Co-Gasification Slag from Municipal Solid Waste and Sewage Sludge: A Novel Supplementary Cementitious Material

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Keywords: Municipal solid waste, Sewage sludge, Co-gasification, Supplementary cementitious material, Waste recycling.

Abstract
The cement industry faces dual challenges of reducing carbon emissions while meeting growing infrastructure demands, as traditional supplementary cementitious materials (SCMs) become increasingly scarce. Simultaneously, municipalities worldwide struggle with sustainable management of municipal solid waste (MSW) and sewage sludge. This study investigates a novel SCM derived from co-gasification of these waste streams (GSMSW) that addresses both challenges through waste valorization and cement replacement.
GSMSW was produced via high-temperature slagging gasification of MSW and sewage sludge. Raw materials were initially gasified at 600-800°C using biomass charcoal as auxiliary fuel, followed by melting at 1600-2000°C where metals naturally separated due to density differences. The liquefied ashes were rapidly quenched in water to form a vitrified slag, which was subsequently processed through magnetic separation, drying at 105°C, grinding, and sieving to achieve cement-comparable fineness (≤63 μm).
Material characterization employed X-ray fluorescence (XRF) for chemical composition, X-ray diffraction (XRD) with Rietveld refinement for crystallinity assessment, and solid-state nuclear magnetic resonance (NMR) spectroscopy for glass network structure analysis. Performance evaluation included two testing systems: (1) model systems with GSMSW, calcium hydroxide, calcium carbonate, and calcium sulfate to isolate fundamental reaction mechanisms; and (2) blended cement systems where ordinary Portland cement (OPC) was partially replaced with GSMSW at 20% and 50% by mass. Isothermal calorimetry assessed early hydration kinetics, while quantitative XRD tracked phase evolution over time. Compressive strength tests were performed on 50 mm mortar cubes at 3, 7, 28, 90, and 180 days, following standard laboratory procedures for cementitious materials evaluation.
Characterization revealed GSMSW to be predominantly amorphous (98.5%) with favorable chemistry for cementitious applications, with combined SiO_2, Al_2O_3, and CaO content exceeding 81%. The high aluminum content (14.17%) compared to OPC (4.4%) was particularly advantageous for enhancing early reactivity. The XRD pattern displayed a characteristic broad hump between 20° and 37° 2θ, indicating short-range order typical of reactive glass structures. NMR spectroscopy demonstrated a moderately depolymerized silicate network with abundant Q^1 and Q^2 sites, creating numerous reactive points for alkaline hydrolysis in the high-pH environment of hydrating cement. This structural configuration proved particularly favorable for reactivity in cementitious systems.
Isothermal calorimetry identified distinct reaction stages in GSMSW-blended systems, with an extended dormant period followed by additional heat evolution peaks at 24-25 and 54 hours that were not present in reference samples. These distinctive peaks confirmed significant pozzolanic activity beyond simple filler effects. Quantitative XRD analysis revealed progressive consumption of both portlandite and GSMSW over the 180-day hydration period. In the 20% replacement mixture, approximately 68% of the initial GSMSW content was consumed by 180 days, while in the 50% replacement mixture, approximately 48% was consumed. The reaction kinetics displayed distinct stages, with the highest consumption rates within the first 49 days, particularly between 7-28 days, followed by a deceleration that coincided with portlandite depletion and modified pore structure.
Compressive strength testing demonstrated that 20% GSMSW replacement achieved strengths comparable to reference samples by 28 days (approximately 52 MPa), indicating significant contribution from GSMSW

reactions. The 50% replacement mixture showed lower early strength but exhibited continued development, reaching approximately 48 MPa by 180 days. The strength development patterns correlated directly with the reaction kinetics observed in microstructural studies, confirming that GSMSW actively participates in the hydration process rather than functioning as an inert filler.

This study establishes co-gasification slag as a technically viable SCM with distinctive structural features contributing to its substantial reactivity in cementitious environments. GSMSW offers a sustainable solution addressing waste management challenges while reducing the carbon footprint of construction materials, particularly effective at moderate replacement levels with immediate practical application potential in various concrete applications.

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Development of a Novel SUHPC Based on PC-CAC-C$ System: Rheology, Early-Age Strength, and Hydration Kinetics

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Abstract:

A novel sprayed ultra-high performance concrete (SUHPC), incorporating a Portland cement-calcium aluminate cement-gypsum (PC-CAC-C$) ternary system was developed to address rheology, shrinkage, and early-age strength challenges. Investigations employing QXRD, TGA, calorimetry, rheology, and SEM show that a C$/CAC ratio of 0.5 maximizes early ettringite formation, yielding a thixotropy four times higher than poured UHPC and a 3-hour strength of 15.11 MPa. Further incorporation of alkali-free accelerator reduces the initial setting time to under five minutes and increases early strength to 20.37 MPa. At later stages, the accelerator promotes strätlingite formation, mitigating the phase conversion of CAC and preserving strength and durability. Meanwhile, the ternary system induces micro-expansion, effectively offsetting both accelerator-induced shrinkage and autogenous shrinkage of SUHPC, thus ensuring dimensional stability. Overall, the PC-CAC-C$ SUHPC achieves rapid setting, enhanced thixotropy, early strength, and micro-expansion, making it a promising candidate for large-scale shotcrete repair applications.

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Dipotassium hydrogen phosphate activated Al-rich steel slag: the role of layered double hydroxides and aluminum hydrate gel

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Keywords: Steel slag; Dipotassium hydrogen phosphate; Chemical activation; In-situ formed LDHs; Microstructure

The utilization of steel slag as a cementitious material has gained significant attention due to its potential to reduce environmental impact and promote sustainable construction practices. However, aluminum-rich (Al-rich) steel slag often exhibits low early-age strength due to the absence of calcium silicate hydrate (C-S-H) gel and the formation of metastable phases such as C_2AH_8. To address this limitation, chemical activation methods are being explored to enhance its hydraulic reactivity. This study introduces a novel approach using dipotassium hydrogen phosphate (DHP, K_2HPO_4) as an activator to optimize the hydration of Al-rich steel slag. By promoting the formation of layered double hydroxides (LDHs) and aluminum hydroxide (AH_3) gel, this method significantly improves mechanical performance and microstructural refinement, offering a sustainable solution for steel slag valorization.

The study investigates the hydration mechanism of Al-rich steel slag blended with DHP as the sole additive. The hydration kinetics were analyzed using isothermal calorimetry, while phase evolution was characterized via X-ray diffraction (XRD). Microstructural development was examined using scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP) to assess pore structure refinement. The compressive strength of hardened pastes was measured at different curing ages (1, 7, and 28 days). Leaching tests were conducted to evaluate the immobilization of phosphate (PO_4^{3-}) and heavy metals (Cr, V) to ensure environmental safety.

The results demonstrate that DHP significantly enhances early hydration by increasing the pH of the pore solution (11.5–12.0), which favors the formation of Ca-Al-LDHs with phosphate as the interlayer anion (LDHs-PO_4). The presence of phosphate ions (PO_4^{3-}) stabilizes LDHs due to their optimal molecular configuration and divalent charge. Concurrently, DHP suppresses the formation of metastable C_2AH_8, releasing additional $Al(OH)_4^-$ ions that contribute to AH_3 gel formation. This dual mechanism leads to a denser microstructure, characterized by highly crystalline LDHs and amorphous AH_3 gel. Pore structure analysis reveals that DHP reduces the volume of large capillary pores (>100 nm) by up to 27%, enhancing mechanical performance. The 28-day compressive strength reaches 40.54 MPa, a substantial improvement over non-activated steel slag. Leaching tests confirm that phosphate and heavy metals (Cr, V) are effectively immobilized, with negligible environmental release.

This study presents an innovative DHP activation method that enhances the early-age strength and microstructure of Al-rich steel slag by promoting in-situ LDHs and AH_3 gel formation. The optimized pore structure and high compressive strength (40 MPa at 28 days) demonstrate the viability of DHP-activated steel slag as a high-performance cementitious material. Furthermore, the negligible leaching risk of phosphate and heavy metals ensures environmental safety. Future research should focus on assessing the carbonation resistance of DHP-activated steel slag, particularly in harsh environments, to expand its potential applications in sustainable construction.

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Early-age and hardened performances of cement paste with ultra-low dosages of CNF-TiO_2 hydrosols

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Keywords: Nano-dispersed TiO_2 hydrosols; visible-light photocatalytic concrete; rheological behaviours; microstructure

There are still risks to using nano-dispersed TiO_2 hydrosols to prepare cementitious materials because of the inherent acidic properties. The work investigates the negative influences and potential solutions of nano-dispersed TiO_2 hydrosols with ultra-low dosages to cement paste (0.10 % to cement) at an early age and 28-day-age. The cellulose nanofibrils (CNF) are used to modify the TiO_2 hydrosols to prepare the visible-light photocatalysts (CNF-TiO_2 hydrosols).
According to the UV-VIS absorbance spectra of the modified CNF-TiO_2 hydrosols, the bandgap energy values of the synthetic photocatalysts show a linear decrease with the increase of the mass ratios of CNF to TiO_2, which is greater than or equal to 1.0 the modified CNF-TiO_2 hydrosols can be excited by visible light with a wavelength larger than 401.5 nm. The hydrodynamic diameters of the synthetic photocatalysts show an exponential increase with the increase of the mass ratios of CNF to TiO_2, the recommended mass ratios should be less than 2.5 in this work. The coefficients of viscosity of slurry noticeably increase and then slightly decrease with the increase of CNF to TiO_2 mass ratio in hydrosols, while the thixotropic loop areas of slurries show the opposite changing law. Mixing the pure acidic nano TiO_2 hydrosols negatively affects the compressive strength of the hardened paste, fortunately, the CNF-modified TiO_2 hydrosols can offset those negative influences and improve the compressive strength of the hardened cement paste at 1-day-age and 28-day-age. The presence of all CNF-TiO_2 hydrosols inhibits the cement hydration reactions at an early age, but the peak values of heat flow curves of cement paste increase with the mass ratios of CNF to TiO_2 in the modified photocatalysts. The crystal patterns of hydrates in both an early age and 28-day-age are not influenced by using CNF-TiO_2 hydrosols. Based on the TGA results, the CH mass ratios in the paste samples containing pure and modified TiO_2 hydrosols are higher than that in the Ref group, while the non-evaporable water mass ratios are slightly smaller than that in the Ref group. The hardened paste samples containing CNF-TiO_2 hydrosols show lower thermal conductivity values because of the re-distribution of pores in hardened matrix based on the results of MIP analysis. When the mass ratio of CNF to TiO_2 is larger than 1.5: 1, it can be seen from SEM images that pitting holes appear on the surface of CH crystals, showing a certain porous structure. The edges of CH crystals are gradually blurred, and the crystal size of the ettringite and C-S-H phases becomes smaller compared with those in the blank sample. These special porous features of CH and other hydrates can explain the increase of macropores in the hardened paste containing CNF-TiO_2 hydrosols.
In conclusion, cellulose nanofibrils can effectively improve the visible light photocatalytic activity of nano TiO_2 hydrosols. The addition of both pure TiO_2 and CNF-TiO_2 hydrosols does not influence the fluid type of cement paste slurry, which belongs to yield pseudoplastic fluids. Adding 0.10 w/w % of well-designed CNF-TiO_2 hydrosols to cement paste strengthens the hardened cement paste both at an early age and at 28-day-age but does not change the hydrate patterns. When the mass ratio of CNF to TiO_2 is 1.5: 1 in the modified hydrosols, adding it to the cement paste leads to the highest compressive strength increase rate of about 25 % at 28-day-age. The significant reduction of megapores' porosity and increase of macropores'

porosity in the CNF-TiO_2 modified hardened paste sample are the reasons for the improvement of compressive strength values.

Effect of Dune Sand as Sand Replacement on the Mechanical Properties of a new Steel Fiber High Performance Concrete (SFHPC)

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Keywords: Dune sand; physicochemical characterization; mechanical properties, experimental evaluation

The economic recovery plans and the special development plans for Algeria's various regions will generate very high demand for building materials in the short term. In particular, there will be a need for sand, an essential building material that is under pressure on the construction. In response to this increased use of sand and to meet the demand of the huge building sites, there is only one alternative left to consider: the replacement of alluvial sand, either by crushed sand and/or by Saharan dune sand. This last solution (use of dune sands) is the purpose of the present study. In fact, the south-eastern region of Algeria has large deposits of dune sand, which have been little exploited to date. To this end, the rational exploitation of these deposits for construction purposes is of major economic and environmental interest.

In this study, an important deposit dune field located in Ain Ben Naoui site of Biskra (South-eastern region of Algeria), was explored, in order to exhibit its importance in the construction field (Fig.1). The qualitative and quantitative mineral content of sand samples is investigated using X-ray diffraction (XRD), X-ray fluorescence (XRF), UV-vis absorption, reflectance spectroscopy, the physical properties, and SEM/EDX analysis.

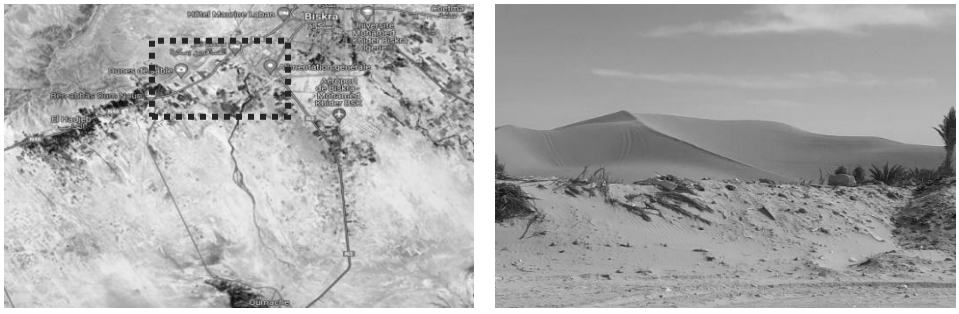

Fig. 1 Dune sand deposit site of Biskra

The main objective is to demonstrate the feasibility of manufacturing Steel Fibre High-Performance Concrete (SFHPC) using dune sand (SFHPC-DS). Formulations have been developed based on dune sand mixtures (DS) incorporating crushed sand (CS) and cement (CEM I-52.5), which is partially replaced by silica fume (SF). Different compositions were prepared and investigated, replacing (by volume) crushed sand with dune sand, with proportions ranging from 0 %, 20 %, 40 %, 60 %, 80 % to 100 %. The hooked ended metal fiber (MF) used was introduced at different concentrations ranging from 0.5, 0.75, 1, 1.25 and 1.50 %. In this work, the SFHPC physical and mechanical characteristics (the compressive, flexural, and splitting tensile strengths) using dune sand (DS) doped artificial (CS) sand are evaluated. The influence of different experimental factors is analyzed.

The results have clearly demonstrated that the SFHPC based with dune sand of Biskra is a highly promising material, since it revealed both good fluidity and better mechanical strengths, with compressive strengths in excess of 60 MPa. The higher compressive strengths of HPSD-DS were obtained in a formulation made with (20 DS + 80 % CS + 10 % FS). After 7 and 28 days of curing, strength gain ratios of 48,38 % and 29,96 % were achieved compared to the sample reference, respectively.

The optimum formula in terms of metal fibre incorporation in the SFHPC-DS matrix was found at an average MF concentration of 1% volumetric quantity. It revealed improved mechanical performance under bending loads and failure mode (resistance to cracking). The ductility indices I5, I10 and I30 increase progressively with increasing steel fiber content. The ductility is significantly higher when the fiber content is doubled. The splitting tensile strength of SFHPC improves with increasing fiber volume fraction. Strength gains of 15.75, 26.31 and 42.1% were obtained when the fiber content was increased from 0.75 % to 1.5 %, respectively.

The failure mode of SFHPC with 0.75 % fiber content is practically the same as that of SFHPC with 1.50% fiber content, except that the crack width of the specimen (at the mid-span zone) is more pronounced than that of SFHPC-1.50. This behavior has changed from a brittle and sudden fracture mode for the reference SFHPC, where the specimens are completely fractured in two, to a progressive and ductile fracture where the SFHPC retains its stability and remains unified in a single block. The reason for this is that the addition of steel fibres to SFHPC results in greater regularity and homogeneity, and offers greater resistance to crack development than those with medium or low fiber content.

SEM observations clearly revealed the failure mechanism at the fibre/matrix level of SFHPC-SD. It begins with a partial fibre pull-out at the break of the complete fibre. In addition, the fiber surface was found to be completely covered with hydration products, resulting in relatively high interfacial adhesion and an effective fiber-bridging effect.

These findings offer a valuable contribution, which provides useful insights that can be used to valorize the dune sand in the field of civil engineering.

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Effect of Fe_2O_3 content on clinkerization of low calcium carbonatable belite-rankinite clinker

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Keywords: Fe_2O_3, rankinite, clinkerization, carbonatable clinker

The development of carbonatable clinkers is a crucial strategy for reducing carbon emissions in the cement industry. Belite-rankinite-based clinker stands out due to its low calcium content, lower clinkerization temperature, self-pulverization characteristics, and inherent ability to absorb CO_2. This study investigates the impact of Fe_2O_3 content on the clinkerization process of low-calcium carbonatable belite-rankinite clinker. The findings reveal that the addition of Fe_2O_3 enhances the clinkerization process by lowering the required temperature and promoting the formation of high-temperature melts. These melts facilitate the reaction between solid C_2S (dicalcium silicate) and liquid SiO_2 (silicon dioxide) to form C_3S_2 (rankinite). The optimal Fe_2O_3 content was identified to be between 2-3 wt.%, as this range minimizes the presence of free calcium oxide (f-CaO) in the clinker. Quenching the clinkers resulted in lower f-CaO content compared to slow cooling.
At high temperatures, the formation of viscous melts creates a local reducing atmosphere, causing the transition of Fe^{3+} to Fe^{2+} ions. During cooling, Fe^{2+} ions substitute Ca^{2+} ions as rankinite precipitates from the melts, leading to an increase in f-CaO content in the clinkers. These insights are expected to provide valuable theoretical guidance for optimizing the design and performance of carbonatable belite-rankinite clinkers. By improving the efficiency of clinker production and reducing energy consumption, this research contributes to lowering CO_2 emissions in the cement industry. This aligns with global sustainable development goals, promoting a more environmentally friendly approach to cement manufacturing.

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Effect of Recycled Glass Fibre Reinforced Polymer on the Mechanical Strength of Cement Mortar

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Keywords : cement mortar, recycled GFRP, workability, mechanical strength

Glass fibre-reinforced polymers, thanks to their high performance combined with low weight, are widely used in many sector. However, at the end of their life cycle, these materials are difficult to recycle, due to the dfficulty of separating the glass fibre from the matrix (thermoset resin). The incorporation of recycled glass fibre reinforced polymer (rGFRP) in cementitious materials is an interesting recycling and valorisation method. This involves cutting glass composites into small pieces and using them as aggregates. However, add rGFRP particles as aggregates in cementitious materials generally leads to reduction in workability and an improvement in certain mechanical performances. The aim of this study is to examine the effect of different size fractions (0.063 mm, 0.16 mm, 0.63 mm, 1.25 mm and 2 mm) of rGFRP on the mechanical behavior of mortar. In this way 10% by volume of the sand is replaced by rGFRP particles. The density of rGFRP particles is lower than that of sand, ranging from 1.6 to 2.7 g/cm^3. Six mortar formulations incorporating rGFRP particles were carried out, varying the particle size in the different mixes. Each formulation is designed by a letter from A to F. Formulations A, C and F consist of a single rGFRP particle size of 0.063 mm, 0.63 mm and 2 mm respectively. For forlumations B, D and E, a mixture of different particle sizes is performed, consisting of 1.25 – 0.16 mm, 1.25 – 0.063 and 0.16 mm respectively, and a complete mixture of all particle sizes for formulation E. Mortars are manufactured in a accordance with standard EN 196–1, in an automated mixer. After manufacture, the consistency is measured (spread diameter), then prismatic samples (4 × 4 × 16 cm^3) are made, for subsequent measurement of density, mechanical behavior, water-accessible porosity and microscopic observation. The results obtained show acceptable workability for all formulations and a decrease in the density of mortars incorporating rGFRP depending on their size, which could be justified by the lower density of rGFRP particles compared with sand particles. Compressive and flexion tests at 7 days and 7 months of curing show a logical inrease in performance over time due to cement hydration. Figure 1a shows the results obtained in compression test, where the values at 7 months all reach 40 Mpa. Figure 1b shows the percentage variation in compressive strength of samples with rGFRP. A reduction in comprssiv strength is observed for all samples although this reduction is less significant for samples E and F (<10%). However, the samples A, which contains only fine particles, shows the greatest reduction in compressive strength, reaching 31%.

Figure 2a shows the results for the flexural strength, with values of around 5 to 6 Mpa at 7 days and 10 Mpa at 7 months curing of sample. Figure 2b shows the variation in flexural strength of samples containing rGFRP. A slight decrease in flexural strength is observed for samples B, C, D and E of less than 10% and a slight improvement of around 2.7% for sample F, which showed less brittle fracture during test. A study of water-accessible porosity after 7 months curing shows a slight increase in porosity for the samples with rGFRP particles, which could account for the drop in density and compressive performance.

Finally, microscopic observation of the samples after 7 months curing reveals the presence of rGFRP particles in the matrix. Particle agglomeration is observed for the formulations with very fine particles (Sample A), and for the formulations containing 2 mm particles (Sample E and F), glass fibre filaments are observed dispersed in the matrix, potentially improving resistance to crack propagation. However, the vast majority of fibres are astill grouped in bundles. Thus, after 7 months of curing, the non-alkali resistant glass fibres remain present and show no degradation.

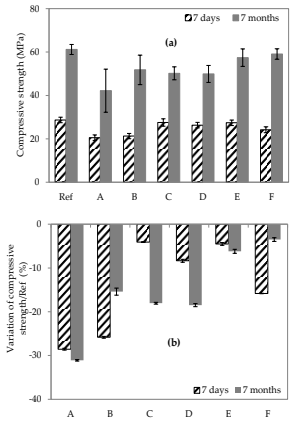

Figure 1. (a) Compressive strength of mortar at 7 days and 7 months, (b) Variation of compressive strength (%) compared to reference mortar

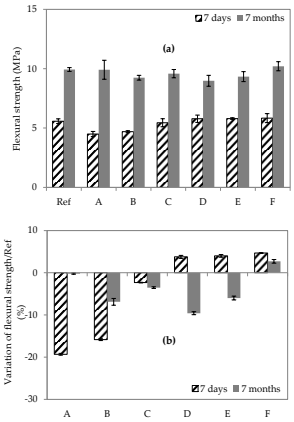

Figure 2. (a) Flexural strength of mortar at 7 days and 7 months, (b) Variation of flexural strength (%) compared to the reference mortar

Enhancement of Flexural Strength of γ-C_2S Carbonated Compacts through In Situ Synthesis of Mg-calcite

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Keywords: γ-C_2S, carbonatable binder, $MgCl_2$, flexural strength, Mg-calcite

Gamma calcium silicate (γ-C_2S) has garnered significant attention as a carbonatable binder due to its rapid and spontaneous reaction with CO_2 in the presence of moisture, forming materials with high compressive strength. This characteristic has rendered γ-C_2S a potential candidate for the development of low-carbon cement alternatives, which are of increasing significance in the context of sustainable construction materials. However, the inherent brittleness of carbonated γ-C_2S compacts, characterized by low tensile and flexural strength, poses a significant challenge to their practical application. To address this issue, this study explores the enhancement of flexural strength in γ-C_2S carbonated compacts through the in situ synthesis of Mg-calcite, leveraging the mechanical and structural benefits associated with Mg-rich calcium carbonate phases.

In this study, highly purified γ-C_2S was synthesized via a solid-state sintering method using analytical-grade $Ca(OH)_2$ and SiO_2 powders. The stoichiometric mixtures were heated at 1400°C for 3 hours and cooled naturally to room temperature. During the cooling process, the γ-C_2S underwent self-pulverization due to thermal stress and volume changes. The synthesized γ-C_2S was then subjected to an aqueous carbonation process, where $MgCl_2$ was introduced at varying concentrations to modulate the formation of Mg-calcite and other calcium carbonate polymorphs. The carbonation process was carried out by mixing γ-C_2S powder with $MgCl_2$ solutions at a water-solid ratio of 0.2 for 2 minutes, followed by compaction into cylindrical and prismatic specimens under a pressure of 30 MPa. The compacted specimens were then subjected to accelerated carbonation in a CO_2 atmosphere at 0.2 MPa for 24 hours.

The mechanical properties of the carbonated compacts were evaluated using an Electro-hydraulic Servo universal testing machine, with the compressive and flexural strengths measured according to standard procedures. The phase assemblages and degree of carbonation (DOC) were characterized using X-ray diffraction (XRD) and thermogravimetry-differential thermogravimetry (TG-DTG). The microstructural and morphological features of the carbonated products were investigated using scanning electron microscopy coupled with energy dispersive spectrometry (SEM-EDS), while the structural properties of silica gels were analyzed using solid-state ^{29}Si nuclear magnetic resonance (NMR) spectroscopy.

The results demonstrate that the incorporation of $MgCl_2$ significantly enhances the mechanical properties of the carbonated compacts. Specifically, the addition of 0.1 mol/L $MgCl_2$ led to a substantial increase in compressive strength (130.3 MPa) and flexural strength (49.0 MPa), indicating improved crack resistance and toughness. This enhancement is attributed to the formation of Mg-calcite and aragonite, which induce structural distortion and internal coherent strain, thereby improving the ability of the carbonated compacts to withstand higher flexural stresses. Additionally, the interaction of Mg^{2+} ions with silica gels promotes the formation of highly polymerized M-S-H structures, resulting in an increased elastic modulus of the carbonated matrix. The DOC also increased with the addition of $MgCl_2$, confirming enhanced CO_2 permeation and sequestration during the carbonation process.

In conclusion, this study presents an innovative strategy for enhancing the toughness of carbonated mineralized materials by regulating the concentration of $MgCl_2$ in the carbonation process. The findings highlight the potential of Mg-calcite as a secondary phase to improve the mechanical properties of γ-C_2S carbonated compacts, thereby broadening their applicability in construction and carbon capture applications. Future work will focus on optimizing the $MgCl_2$ concentration and exploring other potential additives to further enhance the performance of these low-carbon cement alternatives.

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Enhancing Calcium-aluminosilicate SCMs Reactivity: The Impact of Calcium Source and Availability

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Keywords: SCMs, Supply, Degree of reaction, Sources, Calcium silicate hydrates.

Reducing the clinker content in cement through the increased use of supplementary cementitious materials (SCMs) is a key strategy for decarbonising global cement production. The current clinker factor is situated around 0.76 and needs to be further lowered through increased substitution rates and the development of multi-constituent cements. Among the viable alternatives, the use of (calcium)-aluminosilicates SCMs such as metakaolin (MK) and ground granulated blast furnace slag (GGBFS) are of great interest due to their high reactivity. With MK exhibiting pozzolanic characteristics and GGBS displaying latent hydraulic behaviour, their reactivity differs noticeably, with MK displaying significantly higher intrinsic reactivity. Their reaction pathways are strongly influenced by their composition and external calcium supply, which govern the formation of hydrate phases and ultimately control the development of desirable hydrated cement properties and performance.

While previous studies have primarily examined the role of calcium limitation in SCM hydration, the role of Ca-source and limitation remains largely unexplored. Additionally, the contribution of external calcium sources from Portland cement hydrates other than portlandite (CH), such as calcium silicate hydrates (C-S-H), or other Ca sources, e.g. $Ca(NO_3)_2$, have not been systematically investigated. A deeper understanding of the effect of external calcium, solubility and concentration can lead to a better understanding of SCM reactivity, increasing reaction degrees and improving binder efficiency, in particular in Ca-depleted systems such as very low clinker cements.

This study evaluates the reactivity of MK and GGBFS in modulated R^3 model systems at 40°C under conditions of varying CH-to-SCM ratios (3:1, 1:1 and 1:3) to assess the impact of excess and limited Ca-supply on hydration kinetic. Further, CH is replaced with ground hydrated white cement and lab-synthesized C-S-H with varying C/S ratios to investigate the potential of clinker hydration products as alternative Ca-sources for SCMs reaction. Finally, the effect of soluble Ca-salt additions on SCM reactivity is studied. Reactivity is analysed by isothermal calorimetry to record the heat release over a 7-day reaction period. The hydration products assemblage is studied using X-ray powder diffraction combined with an external standard approach for quantitative phase analysis (QPA). Thermogravimetric analysis is carried out to assess the CH consumption and bound water content. Microstructural investigations are conducted via SEM-EDS image analysis, while the degree of reaction (DoR) of MK and GGBFS will be quantified by selective dissolution using nitric acid and EDTA, respectively.

The results indicate that decreasing the CH-to-GGBFS ratio from 3:1 to 1:1 significantly slows GGBFS reactivity despite CH remaining abundantly available in the system. This, combined with electron microscopy observations, suggests that factors beyond CH availability influence reaction kinetics. In particular, the presence of hydrotalcite reaction rims around unreacted GGBFS grains may act as a barrier to further dissolution, thereby slowing down hydration. Ongoing analyses explore whether variations in Ca-supply mechanisms impact the hydration degree of both MK and GGBFS under different conditions of Ca sources and supplies. The findings will clarify how calcium availability influences SCM hydration

mechanisms and contribute to the development of optimized mix designs for more efficient low-clinker cement formulations.

Enhancing the Pozzolanic Reactivity of Dredged Sediments through Thermal Activation and Quenching for Cement Applications

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Keywords: Marine dredged sediments, Supplementary cementitious material, Thermal activation and quenching, Pozzolanic properties, Valorisation

The escalating global demand for cement, driven by rapid urbanization and population growth, has resulted in significant environmental concerns, particularly high carbon dioxide (CO_2) emissions and depletion of natural resources. To mitigate these impacts, investigation on innovative and sustainable alternative supplementary cementitious materials (SCMs) to partially replace ordinary Portland cement (OPC) in construction is necessary. Concurrently, millions of tons of dredged sediments (DS) are excavated annually from ports and waterways to maintain navigational channels, presenting both environmental and economic challenges associated with their disposal. Valorizing DS as a pozzolanic material offers a dual advantage—reducing waste accumulation while promoting sustainable cementitious binders. This study investigates the potential of thermally activated and quenched DS as an SCM through comprehensive physicochemical and mechanical characterization. Calcination was performed at a controlled heating rate of 10°C per minute, followed by rapid cooling by quenching the calcined material in water to enhance its pozzolanic reactivity. The DS were characterized using X-ray diffraction (XRD), thermogravimetric analysis (TGA/DTG), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) to elucidate phase transformations, structural modifications, and alterations in surface morphology. Specific gravity, Specific surface area (SSA) and particle size distribution (PSD) were also measured to evaluate their effect on reactivity. Pozzolanic reactivity was assessed through portlandite consumption in a lime-pozzolan system, while mechanical performance was evaluated by incorporating quenched DS as a partial replacement (10–30%) for OPC in mortar mixtures. The compressive strength of these mortars was tested at different ages to determine the influence of DS replacement on mechanical properties. Additionally, hydration products were analyzed using XRD to understand the microstructural evolution and the role of DS in the cementitious matrix. The results indicate that thermal activation followed by quenching significantly enhances the reactivity of DS by increasing the amorphous phase content and improves specific surface area and particle density. XRD analysis revealed the transformation of illite/muscovite and kaolinite into amorphous aluminosilicate phases, which are crucial for hydration reactions. Furthermore, SSA and PSD measurements confirmed that calcined DS exhibited finer particles with increased surface area, contributing to improved reactivity. Mortars with optimal replacement levels demonstrated mechanical properties comparable to control samples, confirming the viability of thermally activated and quenched DS as a supplementary cementitious material (SCM). These findings underscore the feasibility of utilizing thermally activated and quenched DS as an alternative to conventional SCMs like fly ash, particularly in regions where high-quality SCMs are scarce. The study also emphasizes the environmental benefits of DS valorization, including reduced carbon emissions, conservation of natural resources, and

minimization of sediment disposal challenges. By integrating thermally activated and quenched DS into cementitious systems, this research contributes to advancing sustainable construction practices and promoting circular economy principles in the cement industry.

Evaluating the Strength of Concrete Incorporating Sodium Hydroxide Treated Rubber Crumb and Steel Wire.

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Keywords: Rubber Crumb, Steel Wires, Concrete, Sustainability, Compressive and Tensile Strength

Abstract

The ability of structural members in a building to perform their intending functions is a way of evaluating the structural performance and integrity of the whole building. As a matter of fact, the structural deterioration of concrete structures has emanated in the construction industries due to poor mixed design, workability, choice of materials and inefficient quality control during the batching process. These defects have resulted into many failures and collapses within the global system. The problem of wastes disposal and effective management schemes in the global communities is continually on the increase. Recently, the high rate of tyres being dumped as scraps into landfills has been causing a lot of environmental issues. One of the visions of the circular economy campaign is infusing solid waste into the development of composites as alternatives to its ingredients. The incorporation of scraps tyres (ST) alongside its in-built steel fibre wires in concrete is one of the approaches towards mitigating the problems of waste management and consequently, improving the performance of the composites. Thus, this research focused on enhancing the compressive and tensile strength of concrete with the incorporation of sodium hydroxide (NaOH) treated rubber crumb (RC) and the steel fibre wires (SW) extracted from the scraps of Off Road Tyres (ORT) during its shredding into crumbs. The RC-SW-concrete was produced using a mix ratio of 1:2:3 (cement: sand: granite) and 0.43 as the water – cement ratio, 1.5%, 2.5%, 3.5%, 5.0% of RC by the weight of cement and 3.0% of SW as fibres, and Optima 206 superplasticizer as chemical admixture applied to increase the workability of RC - SW - concrete. The workability, consistency and setting times of the RC – SW - concrete and cement pastes were determined through the slump test and the use of Vicat apparatus according to SANS 5862-1: 2006 and SANS 50196 – 3 standards. Also, the compressive and tensile strength of RC-SW-concrete were determined through the crushing of 150 x 150 x 150 mm RC-SW-concrete cubes and 150 x 300 mm RC-SW-concrete cylinders at 7 and 28 days of water curing in accordance with SANS 5862 – 1: 2006 and SANS 5863: 2006 standards. The workability of RC-SW-concrete were recorded in the range of 80 – 100 mm, which is referred to as true slump. In addition, the optimum compressive strength was obtained with incorporation of a binary combination of 1.5 % RC and 3.0% SW in concrete with the corresponding strengths of 71.75 MPa and 84.87 MPa at curing duration of 7 and 28 days, respectively. Also, the concrete with 2.5% and 1.5 % of RC with 3.0% SW produced the optimum tensile strengths of 8.43 MPa and 9.73 MPa at 7 and 28 days of curing. In addition, the compressive strengths of RC-SW-concrete were more than that of controls by 1.03% at incorporation of 1.5% of RC and 3.0% of SW at 7 days of curing. Also, the 28 days RC-SW-concrete's compressive strengths increased by 5.86% and 1.28% than that of the control at 1.5% and 3.5% of RC with 3.0% of SW. Likewise, the tensile strengths of RC-SW-concrete are by 7.60%, 6.11% and 3.55% more than that of control at 1.5%, 2.5% and 3.5% of RC

with 3.0% of SW respectively. In conclusion, the incorporation of 1.5 – 3.5% of RC with 3.0% of SW in concrete improved its compressive and tensile properties. Thus, the incorporation of RC-SW in concrete is good for the production of high strength concrete for the construction of sustainable buildings, bridges and other infrastructures.

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Evaluation of modified ceramic waste incorporating nanosilica addition for concrete utilization

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Keywords: ceramic waste powder, nanosilica, hydrophobization, concrete, reaction monitoring

The construction sector is experiencing enhancements in environmental regulations, both locally and globally, due to its influence on overall carbon emissions, particularly from clinker manufacturing temperatures. This domain assesses industrial waste and alternative materials owing to their significant application potential and facilitates the evaluation of environmentally sustainable methods concerning consumption volumes. Interest in the construction sector has surged, resulting in the utilization and disposal of diverse industrial waste materials in recent years. Moreover, an opportunity has been identified to utilize these components to enhance the quality of concrete. The research project focused on ceramic waste powder (CWP) as a possible aggregate because of its durability and high manufacturing volume and nano silica was utilized to enhance concrete performance. The ceramic manufacturing process is a high-temperature procedure, similar to cement production. In ceramic manufacturing process defective products regarding shape or decoration identified during production are prevented from market release and assessed in alternative applications. This study aims to define CWP in terms of its composition, size, and activity, and to evaluate the feasibility of using CWP as a partial replacement af iller in the performance of both fresh and hardened concrete. CWP was utilized in both its unprocessed state and after being ground and hydrophobized to diminish its water absorption. A commercially available silane-based chemical was utilized for hydrophobicity. In this investigation, the composition of CWP remained constant, however the nano silica concentration was regarded as changeable. The incorporation of nano silica was anticipated to enhance strength. To determine the impact of the hydrophobicity agent on the concrete samples, the capillary water absorption test was conducted on all samples in accordance with the EN 1015-18 standard. Fresh mortar tests were conducted to assess the mortar's properties. The setting time was assessed in accordance with the EN 196-3 standard, flow was measured according EN 13395-1, and mortar density was determined according to the EN 1015-6 standard. Cured mortar tests were conducted according to EN 12190 standard for flexural and compressive strength assessments at 2, 7, and 28 days after curing. XRD, XRF, and FTIR analyses were conducted to ascertain the mineralogical composition and reaction process. The composition of ceramic waste and cement was analyzed using Rietveld software via X-ray diffraction (XRD). Furthermore, the diminution of cement phases was assessed by XRD analysis during the reaction monitoring, while the hydrated phases generated from the reaction were evaluated using XRF and FTIR studies. The relationship between microstructure and performance was established by examining the reaction progress and strength metrics.

In the CWP sample utilized without hydrophobization, an increase was noted in samples containing up to 1% nanosilica, whereas a decline in early strength was recorded with greater nanosilica concentrations. The CWP samples subjected to hydrophobization exhibited enhanced early strength with a nanosilica content of up to 0.5%, whereas strength diminished at elevated concentrations.

The market applicability of the study is also dependent upon its economic accessibility. The hydrophobicity agent and nano silica utilized in the study are costly components due to their chemical production. In this situation, CWP may serve as a filler alternative in non-structural parts rather than in structural parts. Also, usage of additives that enhance strength and hence elevate prices can be preferred in structural applications. Future research would benefit from utilizing floor tiles with less water absorption capacity by replacing them with certain amount of cement.

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Fine Aggregate Size Optimization of PCM-Loaded LCA for Sustainable Thermal Energy Storage in Construction

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Keywords: Thermal energy storage, PCM-loaded LCA (PLCA), Fine aggregate size optimization, Cementitious composite performance

The integration of phase change materials (PCM) in construction materials has been widely explored for its potential to enhance thermal energy storage and regulate indoor temperatures. However, practical applications remain limited due to PCM leakage, low mechanical strength, and inadequate thermal conductivity. This study introduces a novel loess-based ceramic aggregate (LCA) as an integrated PCM carrier, designed to enhance both structural integrity and thermal performance for real-world implementation. Unlike conventional PCM incorporation techniques, which often act as passive fillers, LCA was systematically optimized by evaluating fine aggregate size and porosity to actively contribute to the mechanical and thermal efficiency of cementitious composites. By precisely controlling fine aggregate size distribution and adjusting porous microstructure, LCA enables enhanced PCM retention, improved structural stability, and efficient heat transfer, making it a scalable and commercially viable solution for energy-efficient construction.

LCA was fabricated using a high-temperature sintering and rapid quenching process, producing a porous framework suitable for PCM encapsulation. To ensure stable PCM retention, a vacuum-assisted impregnation technique was employed, where molten PCM was absorbed into the LCA's porous network under controlled pressure conditions. The resulting PCM-loaded LCA (PLCA) underwent multi-stage filtration to remove excess PCM, preventing surface leakage while ensuring compatibility with cementitious composites. The study further investigated how fine aggregate size affects PLCA performance, revealing that smaller aggregates exhibited higher PCM retention, while larger aggregates provided enhanced mechanical strength, highlighting the significance of aggregate size optimization. Testing of the PCM impregnation rate for the optimized PLCA confirmed a stable retention of 12.3% per unit aggregate, demonstrating its high storage capacity and integration feasibility within cementitious composites.

To address the low thermal conductivity of PCM-based materials, exfoliated graphene nanoplatelets (xGnP) were incorporated into the cementitious matrix, facilitating improved heat transfer and rapid thermal response. The performance of PLCA-enhanced composites was assessed by replacing fine aggregates in cement mortar at varying proportions (20%, 40%, 60%, 80%, and 100%). Compressive strength (CS) tests were conducted at 7 and 28 days, while thermal conductivity (TC) measurements at 10°C, 20°C, and 30°C evaluated insulation efficiency. A novel compressive strength-to-thermal conductivity ratio (CTR) was introduced to quantify the balance between mechanical integrity and thermal efficiency. The results demonstrated that the optimal PLCA replacement ratio was 60%, achieving a compressive strength of 23.8 MPa while reducing thermal conductivity by 38% compared to conventional mortar.

A major contribution of this study is its scalability and commercial viability. By serving as a high-performance alternative to traditional lightweight aggregates, PLCA enables energy-efficient buildings by actively regulating thermal loads, thereby reducing reliance on HVAC systems. Additionally, its cost-effective manufacturing process, utilizing abundant loess resources, establishes PLCA as a sustainable and practical substitute for conventional insulation materials.

This study establishes PLCA as a structurally stable and commercially applicable PCM carrier, providing a breakthrough solution for thermal energy storage in construction. The findings demonstrate that PLCA achieves a well-balanced combination of structural integrity and thermal efficiency, making it a promising alternative to conventional lightweight aggregates. However, to ensure that this performance equilibrium is maintained over time, future research will investigate the long-term evolution of PLCA's structural and thermal properties under real-world environmental conditions. This includes assessing durability factors such as UV exposure, moisture ingress, and thermal cycling, while monitoring potential changes in compressive strength and thermal conductivity over extended periods. Furthermore, long-term durability assessments will be conducted to determine how environmental stressors influence PLCA's mechanical and thermal stability. In parallel, coating technologies and xGnP surface modifications will be explored as potential strategies to enhance PLCA's resistance to environmental degradation, ensuring prolonged functionality without compromising its initial performance balance.

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From Toxic Waste to Sustainable Building: Red Mud Cementitious Composites for Environmental Remediation

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Keywords: Photocatalytic activity, NO abatement, red mud, cementitious mortars, engineering properties

Introduction and scope

Ongoing research on red mud (RM), a by-product of aluminium industry, explores its use in cement production, as a substitute replacing cement in cementitious mixtures as well as its application in geopolymer concrete. Red mud poses a significant environmental threat due to high alkalinity and the presence of heavy metals, which render it toxic. The objective of this study is to evaluate RM as low-cost and an effective photocatalyst for air pollutant degradation. The potential of RM as photocatalyst stems from its diverse chemical composition, particularly its high content of iron oxide. The photocatalytic capability allows materials to break down harmful pollutants in the environment through light-driven chemical processes. By integrating RM into cementitious materials, authors aim to develop dual-purpose building materials that both support structures and clean the environment through photocatalysis, potentially revolutionizing sustainable construction practices and increasing the circular economy by reusing a waste material.

Experimental Framework

The chemical composition of binders i.e., CEM III 42.5 SR, oven-dried red mud (RM-OD) and red mud incinerated at 600°C (RM-I), is presented in Table 1. A standard 1:3 cement-sand mortar with 0.5 w/c served as control mix. Six mixtures were prepared by replacing cement with two types of RM at 5%, 10%, and 15% by weight. Specimens were cast to determine the compressive and flexural strength in compliance with BS EN 1015-11:2019.

The isothermal calorimetry data was collected using a TAM AIR microcalorimeter at 25°C. About 10 g of paste was quickly prepared and placed in the calorimeter for measurement.

Mercury intrusion porosimetry was employed to analyse the pore structure of the hardened mortars. The examination was conducted using a Micromeritics AutoPore IV 9500 device, applying pressures ranging from 0.0015 to 207 MPa on mortar fragments.

To assess red mud's potential as a photocatalyst, nitrogen oxide (NO) abatement tests are conducted on mortar samples. The photoreactor is fed by a 0.78 L min^{-1} flow of NO and air with an initial NO concentration of 500 ppb. After 30-minute equilibration period to account for surface adsorption, samples underwent a one-hour illumination using a 300 W Ultravitalux lamp.

Table 1: Chemical composition of cement and red mud (RM-OD and RM-I).

Element oxides (%)	CEM III	RM-OD	RM-I	Element oxides (%)	CEM III	RM-OD	RM-I
CaO	58.39	3.44	3.43	MnO	0.13	0.12	0.12

MgO	3.81	0.34	0.44	ZrO_2	0.03	0.34	0.29
Al_2O_3	7.47	16.33	16.1	SrO	0.13	0.02	0.02
SiO_2	21.22	7.01	6.81	TiO_2	0.50	8.30	7.61
Fe_2O_3	2.58	58.94	59.88	V_2O_5	0.03	0.33	0.31
SO_3	4.25	0.49	0.5	Cr_2O_3	0.03	0.32	0.32
K_2O	1.00	0.11	0.07	Sc_2O_3	0.29	-	-
Na_2O	-	3.71	3.94				

Results and discussion

Heat of hydration, mechanical strength, porosity

The impact of RM on cement hydration is discussed through heat flow curves (Fig. 1). Incorporating RM reduces peak and cumulative hydration heat while delaying peak hydration time (Table 2). The third peak in heat flow curve is particularly affected by RM content, with higher concentrations leading to earlier and more intense peaks. The full width at half maximum (FWHM) values decrease as RM content increases, indicating faster and more concentrated hydration product formation. In contrast, control samples and those with low RM content (5%) show higher FWHM values, suggesting a more gradual hydration process.

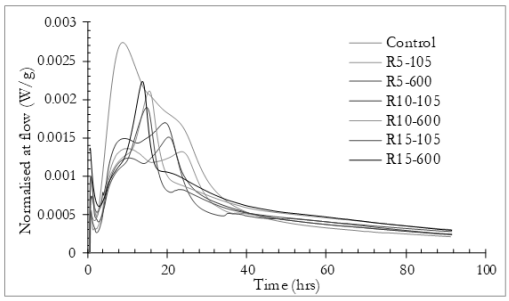

Fig.1: Heat flow curves of mortars investigated in the study.

Table 2: Isothermal calorimetry test results of mortars.

Mix	Start of acceleration period (in hrs:min:sec)	Normalised heat flow at start of acceleration (mW/g)	Arrival time of prominent exothermic peak (in hrs:min:sec)	Normalised heat flow corresponding to prominent exothermic peak (mW/g)	Cumulative heat released at 72 h (J/g)	FWHM value (in hrs:min)
Control	1:49:18	0.42131	8:52:07	273,899	238.22	19:30
R5-105	1:27:49	0.30001	10:23:15	135,921	164.42	23:00
R10-105	2:29:56	0.52784	19:28:03	169,567	179.79	18:00

R15-105	2:47:20	0.40464	14:56:08	189,263	161.93	8:30
R5-600	2:19:10	0.26542	10:28:15	123,611	154.52	19:00
R10-600	2:14:39	0.46450	15:34:27	210,730	182.61	8:30
R15-600	2:54:14	0.60670	13:50:18	223,199	189.83	5:30
Typical nomenclature for the investigated mortar mix is represented as RX-Y, where X represents replacement levels of cement with RM (5, 10 or 15), and Y represents the treated temperature (either 105°C or 600°C).						

Mortars with up to 10% RM-OD performed similarly to the control mix, while those with RM-I showed slight improvements in early strength. However, 15% RM substitution led to decreased strength, and while RM's alkalinity accelerates early hydration, it negatively impacts long-term strength development.

The 28-day compressive strength of R5-105 is similar to control mix. As RM substitution increased, 28-day compressive strength decreased, with RM-OD and RM-I showing 20-44% and 17-30% drop, respectively. This reduction is attributed to dilution of cement, red mud's inert nature and increased porosity of cementitious matrix.

Mortars incorporating RM showed improved 7-day flexural strength compared to control mix, with RM-I-based mortars performing better than RM-OD counterparts. However, at 28 days, mortars with higher RM content (15%) experienced a reduction in flexural strength, though not as significant as the drop in compressive strength.

The addition of RM increases porosity due to relatively bigger pores (Table 3). It contains less calcium oxide and silica, which are responsible for strength development and pore refinement in cement-based materials. The lower content of these compounds in RM resulted in more porous microstructure.

Table 3: Engineering properties of investigated mortars.

Sample ID	Compressive strength		Flexural strength		Pore size distribution (MIP)			
	7-day	28-day	7-day	28-day	<20 nm	20-50 nm	50-200 nm	>200 nm
Control	21.56	37.00	6.59	7.40	20.75	24.13	28.92	20.75
R5-105	22.41 (23.59)*	37.38 (39.35)*	7.25	7.25	24.81	30.84	20.52	23.84
R10-105	20.30 (22.56)*	29.80 (33.11)*	6.80	7.20	17.36	36.38	21.21	25.05
R15-105	16.54 (19.46)*	20.59 (24.22)*	6.54	6.10	28.87	32.74	17.48	20.90

R5-600	22.19 (23.36)*	29.94 (32.01)*	6.93	7.96	39.44	18.10	10.49	31.97
R10-600	23.33 (25.92)*	29.70 (33.48)*	7.4	7.73	41.96	21.78	11.12	25.13
R15-600	19.90 (23.41)*	25.41 (30.47)*	7.31	6.57	46.15	22.68	10.16	21.01
*Values in parentheses indicates the normalised compressive strength.								

Photocatalytic activity test

UNE 127197-1:2013 categorizes effectiveness of photocatalytic materials in cementitious products for air purification into four classes based on their NO degradation capability. Class 3 is labelled as most effective with purification rate greater than 8%. All mortars belong to Class 3 in terms of their effectiveness to degrade the pollutant gas (Table 4). Substrate properties like roughness, surface area, porosity, and alkalinity significantly affect mortars' photocatalytic NO removal. High alkalinity of RM boosts photocatalytic activity by generating more reactive radicals. Pore-size distribution analysis reveals that RM-OD mortars have higher proportion of pores (50 nm and above) compared to RM-I counterparts. Bigger pores facilitate better mass transfer, allowing reactants to easily access active sites thus impacting overall catalytic efficiency.

Table 4: Percentage abatement of NO and NOx for RM-based mortars under solar irradiation and visible light.

Sample ID	Percentage abatement	
	NO	NOx
R5-105	10.2	10.6
R5-105-F	9.4	9.2
R10-105	17.1	16.5
R10-105-F	14.3	14
R15-105	20.4	18.9
R15-105-F	14	13.7
R5-600	9.1	8.4
R5-600-F	9.7	9.6
R10-600	15.8	14.1
R10-600-F	10.2	9.1
R15-600	14.5	13.8

R15-600-F	8.1	7.3
NO and NOx percentage abatement values for samples with abbreviation with letter 'F' at end indicates these samples are tested under strict visible light irradiation.		

Conclusion

Red mud's potential benefit as a filler for particle packing is outweighed by its reactivity, alkalinity and hydration characteristics, which ultimately hinder its contribution to strength development. Cementitious materials containing RM have potential of reducing NO when exposed to solar radiation and visible light.

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Functionalizing construction materials with waste glass

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Keywords: Lightweight; Superhydrophobic; Permeable; Photocatalytic; Self-healing; Stabilization and solidification.

Waste glass beverage bottles are a major solid waste type in Hong Kong. This abstract shows our works on the utilization of municipal waste glass for functionalizing construction materials, including self-healing ultra high-performance concrete, high-strength lightweight concrete, superhydrophobic foam concrete, photocatalytic permeable concrete, and low-carbon concrete for heavy metals stabilization and solidification. We explored the beneficial role of waste glass powder (WGP) in mitigating thermal damage and ultra-high performance concrete (UHPC) after elevated temperature exposure. The presence of WGP significantly enhanced the residual mechanical properties of UHPC due to more wollastonite generation. The WGP also facilitated the recovery of mechanical properties and surface morphology during the post-fire self-healing process. Incorporating lightweight materials into glass-based UHPC can produce durable high performance lightweight concrete (HPLC), characterized by low density, ultra high strength and superior durability. The utilization of waste glass in forms of powder and cullet was able to make a desirable UHPC binder for HPLC. The adoption of tailored high-strength core-shell lightweight aggregates contributed to developing low-carbon HPLC, which has been successfully applied in the modular integrated construction units. Moreover, combining the WGP with other solid wastes, such as incinerated sewage sludge and bottom ashes, can develop high-strength lightweight aggregates for the HPLC production. Apart from solid wastes, waste flue gas (CO_2) bubbles were also introduced into cement paste for preparing a high-strength foam concrete. In addition, a superhydrophobic structure was designed to further improve the durability of foamed concrete. For permeable concrete, an ultra-high-strength mortar incorporating WGP and waste glass aggregate was developed to enhance aggregate bonding in permeable concrete. A high-performance permeable concrete, with a compressive strength exceeding 50 MPa and satisfactory permeability, can be achieved. Structurally, a robust ternary composite cover with steel reinforcement was introduced, significantly improving the load-bearing capacity. This permeable cover has been implemented in a pilot-scale demonstration, with meeting Class F requirements according to the FACTA standard. We also developed a high-strength photocatalytic permeable concrete (HSPPC) with waste glass, and employed a low-pressure cold spraying method to apply the photocatalyst to its surface, enhancing the durability of the photocatalytic coating through synergistic optimization of both the materials and spraying process. The efficiency of NO removal was increased with the increase in the amount of photocatalyst and aggregates. Compared to ordinary pervious concrete, the resistance to seepage scouring and vehicle tire abrasion of HSPPC was significantly improved. Moreover, the combination of HSPPC and the cold spraying method

resulted in an efficient synergistic effect, considerably enhancing the durability of the photocatalyst compared to traditional brushing methods. As some glass types are hazardous material, such as cathode ray tubes (CRT) glass, we also developed a novel glass-based supersulfated cement (SSC) prepared with waste phosphogypsum for the stabilization and solidification of heave metals. The SSC provided a more promising outlet for the recycled CRT glass compared to OPC cementitious system in terms of environmental impacts (leaching and carbon footprint). The joint use of low carbon SSC and CRT glass can not only reduce 80% CO_2 emissions by realizing the valorization of multiple types of solid wastes but also achieve better durability over the OPC system. This presentation will provide substantial solutions for recycling waste glass to reduce carbon emissions and enhance the performance of concrete, which would be promising for practical applications in functional constructions.

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Fundamental Understanding of the Carbonation of Tricalcium Aluminates

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Keywords: wet carbonation, reaction kinetics, precipitation, CO_2 solubility

Global CO_2 emissions from the cement industry are expected to rise in the coming years due to population growth, infrastructure development, and urbanization patterns. One of the mitigation techniques to address this issue is the implementation of carbon capture and utilization (CCU) technologies, which are expected to reduce global CO_2 emissions by 42% in 2050. Enforced carbonation has emerged as a potential method for enhancing the properties of Portland cement. Several studies showed the successful carbonation of Portland cement, where major phases like calcium silicates fully carbonate, minor phases like tri-calcium aluminates (C_3A) do not exhibit the same behaviour. Therefore, a comprehensive analysis of the factors limiting the carbonation of C_3A is essential to understand their reaction kinetics and mechanisms. In this study, large quantities of pure phase C_3A were synthesized at temperatures around 1400°C-1450°C in a high-temperature clinkering furnace. The purity of the phases was evaluated using an array of characterization techniques such as x-ray diffraction (QXRD), X-ray Fluorescence (XRF), Fourier transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA). Samples with purities up to 97% were selected for subsequent experiments. The carbonation experiments were conducted under aqueous conditions, i.e., high water to binder ratio. To determine the optimal operating conditions, several factors were varied, including the pH of the initial solution, CO_2 concentration, pre-hydration time, temperature, and carbonation duration. Geomodelling software like PHREEQC was utilized to calculate saturation indexes and optimize laboratory experiments. The reaction products and solution compositions were also analysed using QXRD, TGA, FTIR, scanning electron microscope (SEM), and inductively coupled plasma optical emission spectroscopy (ICP-OES). The in-situ pH measurements provided valuable insights into the complex reactions and various stages involved in C_3A carbonation. Higher CO_2 concentration and longer pre-hydration time resulted in a higher carbonation degree. The carbonation products were mainly calcium carbonate, unreacted C_3A, and varying amounts of amorphous content with different morphologies. The dissolution of the anhydrous C_3A, the precipitation of products, and the solubility of CO_2 gas have significant effects on the carbonation reaction mechanism, indicating distinct kinetic and thermodynamic limitations. Overall, this study will facilitate the development of solubility diagrams and the exploration of the C_3A surface and its interactions with sulfate and carbonate species. Furthermore, the experimental results will provide the basis for developing effective methods to improve calcium aluminate carbonation by addressing its limitations. Enforced carbonation has the potential to transform carbonated materials into valuable supplementary cementitious materials, significantly promoting circular economy principles within the construction industry.

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Hydration and strength development of very low clinker ternary slag-limestone cement

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Keywords: Low clinker cement; Slag, Limestone, Hydration; Compressive strength.

Reducing clinker content to well below 50% in cement, known as very low clinker (VLC) cements, is a promising way to lower CO_2 emissions in the construction industry. This reduction can be achieved by replacing clinker with supplementary cementitious materials (SCMs), such as fly ash, blast furnace slag, limestone, calcined clay, and natural pozzolans. However, despite ongoing efforts, the global average clinker level remains around 75%, with little reduction over the past decade. Further reductions of clinker content are hindered by the limited supplies of well-known and accepted SCMs such as ground granulated blast furnace slag and coal combustion fly ashes, but also by lower early-age strength and incomplete understanding of SCM reactivity in VLC cement. Ternary cements incorporating limestone have shown potential in maintaining mechanical performance while enabling further reductions in clinker content. In order to provide experimental dataset to underpin the development of the next generation of VLC cements, this study investigates the effect of clinker content (100%, 70%, 50%, 35%, and 20%) on the hydration kinetics, products and strength development of VLC ternary slag-limestone cements at a water-to-binder ratio of 0.4.

The heat of hydration was measured by isothermal calorimetry at 20 °C for 7 days. The compressive strength of mortars were tested at 2, 7, 28, 90, and 180 days at a loading rate of 2.4 kN/s. The reaction product assemblage was investigated by X-ray diffraction (XRD). Rietveld refinement was performed using Topas Academic software, with rutile as an external standard. Thermogravimetric analysis (TGA) was conducted to quantify bound water and $Ca(OH)_2$ content. Mercury intrusion porosimetry (MIP) was applied to characterize the pore structure. The reaction degree of the slag was measured by selective dissolution technique using ethylene diamine tetraacetic acid (EDTA) solution.

The results showed that lower clinker content decreased total heat release due to the dilution effect, while the higher SCM contents promoted the hydration of clinker phases due to the filler effect. A lower clinker content resulted in reduced early-age compressive strength at 2 days, as well as lower strength development after 28 days. MIP results indicated that clinker content dominated early-age porosity, while the contribution of SCM hydration to porosity significantly increased at later ages. Early-age strength was controlled by clinker content due to the slow reaction of SCMs. At the later ages, TGA and reaction degree analyses demonstrated that the slag reaction was limited by the availability of $Ca(OH)_2$ in VLC cements, thereby limiting long-term strength development. Nevertheless, VLC cement with 35% clinker showed acceptable compressive strength (2 d strength of 12.3 MPa, 28 d strength of 50.8 MPa, and 180 d strength of 57.2 MPa).

Notably, the replacement of 15% slag with limestone did not compromise compressive strength. Compared to the hydration products in the reference pure Portland cement (PC) system, the addition of slag induced

more monosulfoaluminate (Ms) and hydrotalcite formation. In ternary system, Ms disappeared while significant hemicarboaluminate (Hc) and monocarboaluminate (Mc) were detected with the incorporation of limestone, which was beneficial for ettringite retention. The MIP results further indicated that replacing slag with limestone contributes to pore structure refinement in VLC ternary cement.

These findings highlight the influence of clinker content on both the early and long-term performance of VLC ternary cements, providing insights for optimizing the mechanical properties of VLC cement. Strategies such as optimizing particle packing and using accelerating additives to enhance strength may help overcome the current limitations of VLC cement systems.

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Impact of Glass Waste from Household and Electronic Appliances on Cement Hydration and Structure

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Keywords: glass waste from household and electronic appliances; cement hydration; structure; physical and mechanical properties.

Due to the significant increase in consumerism, the amount of household and electronic appliance waste is growing, with particularly large amounts of glass waste from such devices. While glass from window or bottle can be sorted and recycled, the reuse of glass from household and electronic appliances remains one of the challenges of sustainable development due to its different chemical composition. Unrecycled glass waste ends up in general landfills, posing an environmental threat worldwide as it is a nonbiodegradable material with a long decomposition period. This study presents the possibilities and challenges of using hard-to-recycle glass waste from electronic appliances and household appliances in the production of a binder with a reduced cement content, as one of the largest sources of greenhouse gas emissions is associated with the production of construction materials. The manufacture of widely used Portland cement alone accounts for approximately 8% of total global CO_2 emissions. The study analyses the properties of three different types of electronic and household appliance glass waste: old television screens (TV), washing machine glass (WM) and luminescent lamp glass (LL). The chemical and mineral compositions, particle size distribution and morphology of these glass types were examined. The chemical composition of the glass types analysed varies significantly: TV glass consists of 53.1% SiO_2, 8.6% BaO, 7.9% K_2O, 7.7% SrO and 6.4% Na_2O; WM glass contains 81.1% SiO_2, 6.5% Na_2O, 3.7% CaO, 3.7% CO_2, and 2.9% Al_2O_3; while LL glass is composed of 67.9% SiO_2, 14.2% Na_2O, 5.5% CaO, 4.0% CO_2, 2.5% MgO, and 2.1% Al_2O_3. Scanning electron microscopy (SEM) analysis has determined that certain types of glass particles can partially crystallise, forming needle-like crystals. When part of the cement (10%, 20% and 30%) is replaced with these glass waste, the cement hydration rate changes: WM accelerates cement setting time, while TV glass slows it down. Numerous glass particle agglomerates form in the microstructure of the samples, increasing the porosity of the cement matrix and reducing the strength. However, over time, the surfaces of the glass particles dissolve, forming new cement hydrates that gradually fill the voids. Due to this process, the density and compressive strength of the cement samples increase significantly after 90 days compared to the curing periods of 7 and 28 days. For example, the compressive strength of samples with WM glass increased from approximately 62 MPa (after 7 days) to about 96 MPa (after 90 days). After 7 days, this strength is similar to that of control samples without glass additives, but after 90 days, it is about 10% higher when 20% of the cement is replaced. The compressive strength of the samples containing other types of glass was approximately 10% lower than that of the control samples, even after 90 days, which was influenced by differences in microstructure formation.
The study also examines the effect of different types of glass on flowability, with results indicating that TV glass reduces flowability the most and these compositions also exhibited the lowest strength. The results show that increasing the amount of glass waste, regardless of its type, decreases flowability due to the irregular shape of the particles, which increases friction between the particles and traps air in the cement mixture. In addition, a larger amount of fine particles requires more water to wet their surfaces. X-ray

diffraction (XRD) and thermal analysis (TG and DTG) were performed after 7, 28, and 90 days of curing of the sample. XRD analysis confirmed that as the curing time increases, the intensity of the main peaks of portlandite and cement minerals decreases due to ongoing pozzolanic reactions, with the greatest reduction observed in WM glass samples, which exhibited the most significant positive effects on all properties. DTG analysis confirmed the pozzolanic reaction and differences between the types of glass used. The amount of portlandite decreased the most in the WM samples, and these samples also had the highest mass losses in the 110-350 °C range, where mass loss occurs due to the decomposition of cement hydration products, including CSH and CASH.

It was determined that different types of glass waste cannot be used as identical additives because of their distinct chemical and mineral compositions and their varying effects on the cement hydration, structure, and physical-mechanical properties of the binder. The best positive effect was observed in samples with WM glass, which is not only amorphous and also initiates an active pozzolanic reaction, promoting greater formation of the CSH and CASH phases and improving the mechanical properties.

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Influence of Biofuel Bottom Ash and Chemical Additives on Hydration and Physical, Mechanical Properties of Cementitious Materials

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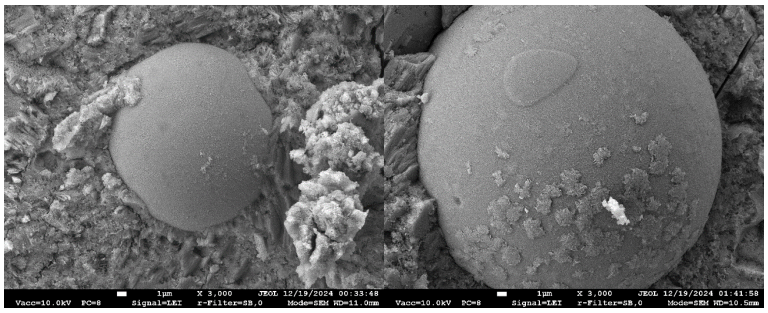
Keywords: Cement, biofuel bottom ash, hydration, consistency, physical and mechanical properties.

This research contributes to the implementation of the Sustainable Development Goals of the United Nations by fostering innovation in the construction sector and supporting the development of more sustainable and resilient cities. The use of waste and additives in cementitious materials is in line with the principles of circular economy, reducing the demand for primary raw materials and promoting responsible use of resources. Furthermore, partial replacement of cement with secondary raw materials reduces CO_2 emissions, contributing to mitigation of climate change and the development of environmentally friendly cement mortars, but usually waste has a negative effect on cement properties.
This study utilises biofuel bottom ash in combination with an active crystal nucleus nanoparticle hardening accelerator and a next-generation superplasticizer based on an intelligent cluster system to eliminate the negative effect of biofuel bottom ash on the properties of cementitious materials. Due to the growing construction industry, the demand for cement is constantly increasing, as it is the primary binding material in concrete and mortars. However, cement production is an energy-intensive process that generates a significant amount of CO_2 emissions. To reduce cement consumption and promote sustainable solutions, this study partially replaced cement with biofuel bottom ash by 5% and 10% by mass.
The purpose of the study is to analyse the influence of biofuel bottom ash and chemical additives on the hydration and physical and mechanical properties of cementitious materials and to determine their suitability for partial cement replacement. First, the results of the calorimetry tests; X-ray analysis (XRD), thermal analysis (TG, DTG), morphology analysis using electron scanning microscope (SEM), density and compressive strength of the cement stone are presented. In addition, the compositions with a fine aggregate were prepared to evaluate the properties, according to standards methods, such as consistency, density, compressive and flexural strength, ultrasonic pulse velocity (UPV), and drying shrinkage of fine-grade concrete after 7 and 28 days of curing.
It was determined that the addition of biofuel bottom ash retards cement hydration, whereas the superplasticizer further delays the hydration process of such a composition. However, the introduction of an accelerator eliminates this effect, leading to hydration occurring even faster than that in pure cement. When both a superplasticizer and an accelerator are used together, hydration is still retarded; however, SEM analysis revealed that, over a longer curing period, the biofuel bottom ash particles dissolve and react more actively when both chemical admixtures are present (Figure 1). The cementitious compositions with an accelerator achieve the highest compressive strength at 7 and at 28 days, compared to the reference sample the strength increases about 10% (from 84.7 MPa to 93.5 MPa) and by using a superplasticizer the compressive strength is similar to the refence sample without the addition of biofuel bottom ash. This effect can be attributed to the enhanced activity of the biofuel bottom ash, which was intensified by the chemical admixtures, leading to the formation of a greater amount of C-S-H and resulting in a denser fine-grade concrete structure.
The density and UPV of fine-grade concrete with the applied chemical admixtures changed insignificantly compared to the reference sample. However, the use of chemical admixtures improved the workability of the mixture and the compressive strength increased. The drying shrinkage results showed that samples with

biofuel bottom ash and chemical additives have several times less shrinkage deformation compared to the reference sample.



a) b)

Figure 1. SEM images of BA particle in reference composition (a) and in composition with both chemical additives (b)

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Influence of polyhedral oligomeric silsesquioxane (POSS) on hydration and strength of Portland cement

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Keywords: Mechanical property; Hydration kinetics; Microstructure; POSS.

Organic-inorganic hybrid materials is a new type of composite materials, including the composite of two or more materials, through chemical or physical interaction to connect the nano phase with other phases, resulting in new structural types and functional characteristics, so that the hybrid materials have the advantages of good toughness, good processability and low cost of organic materials. In this study, the influence of POSS at dosage of 0.2 % and 1.0 % on the hydration, strength and microstructure of Portland cement was investigated using analytical techniques such as calorimetry, zeta potential analysis, microstructure analysis , X-ray diffraction (XRD), thermogravimetric analysis (TGA), and scanning electron microscopy (SEM).

First of all, the calorimetric analysis indicates that the addition of POSS can mildly delay the early hydration reaction of cement paste, leading to a decrease in both the hydration heat release rate and the total heat output. Second, in terms of mechanical properties, POSS decreases the early compressive strength of Portland cement mortar at 1 day; however, its effect on the 28-day compressive strength is minimal. In addition, the zeta potential analysis show that the surface of POSS particles carries a large number of negative charges, which may explain their inhibitory effect on the early hydration reaction of Portland cement. In Portland cement, the mineral phase tricalcium silicate (C_3S) undergoes a reaction upon contact with water, leading to the release of significant amounts of calcium (Ca^{2+}) and other metal cations into the cementitious system. POSS particles can attract these positively charged ions, a phenomenon referred to as the "Complexation effect" in previous literature. Furthermore, the the microstructure performance analysis combines traditional water absorption kinetics with mercury intrusion porosimetry (MIP) testing. After 28 days of standard curing, the POSS-Portland cement composite mortar was dried in a vacuum oven for 48 hours, and its water absorption rate over time was measured to characterize the pore structure. At specific dosages (0.2 % to 0.4 %), POSS contributes to the refinement of pore structure, optimizing porosity by promoting the transition from larger to smaller pores due to its dispersion-enhancing effect in cement paste, although its air-entraining behavior results in a slight increase in total porosity. Additionally, selected mortar samples with specific mix proportions underwent mercury intrusion porosimetry (MIP) testing to verify the findings from water absorption kinetics, and a comprehensive analysis integrating both methods was conducted to assess the influence of POSS on the microstructure of Portland cement mortar. Finally, XRD, TG, and SEM analyses were conducted to examine the types, quantities, and morphologies of the hydration products in POSS-Portland cement., and a hydration reaction model was established.

Polyhedral oligomeric silsesquioxane (POSS) is a cage-structured organic-inorganic hybrid material that exhibits both the exceptional stability of inorganic components and the tunability of organic functional groups, drawing significant research interest for its extensive application potential in nanocomposite materials. POSS, as a well-structured silsesquioxane oligomer, demonstrates the cooperative effect between its siloxane core and modifiable external groups, facilitating its distinctive applications at the organic-

inorganic interface. In the field of concrete, there is a growing adoption of novel polymers, especially for crack remediation, including the use of innovative chemical grouting methods. Despite its potential to improve the compatibility between organic and inorganic materials, POSS remains largely underexplored in cementitious material research. Conducting experimental studies on the interaction between POSS and Portland cement is crucial to assessing and confirming the practical applicability of this emerging class of polymer materials.

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Influence of sodium based ligands on carbonate phase tailoring in recycled concrete fines: A comparative study on tripolyphosphate and sodium citrate

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Keywords: Recycled concrete fines, Wet carbonation, Amorphous calcium carbonated, Sodium tripolyphosphate, Sodium citrate.

The concrete waste from demolition takes up significant landfill space, creating a huge environmental burden and highlighting the unsustainability of traditional waste management practices. As a result, innovative methods are urgently needed to address waste disposal challenges and mitigate CO_2 emissions. Research on the upcycling of recycled concrete fines (RCF) through carbonation technology has shown great potential for carbon sequestration, simultaneously allowing carbonated recycled concrete fines (cRCF) to be used as a supplementary cementitious material (SCM). Reducing the use of cement creates a win-win situation for sustainable construction and environmental protection. Recent results show that the carbonated recycled concrete fines primarily consist of calcium carbonate and silica gel. Inspired by these findings, in addition to Si gel, calcium carbonate-based composite is expected to be a novel future cementitious material by controlling the crystallization transformation of calcium carbonate. However, the understanding of using additives to control the pathway of the calcium carbonate polymorphs is limited. Therefore, in order to enhance the reactivity of RCF, this study presents a novel approach to control the calcium carbonate formation pathways by using sodium based ligands under the wet carbonation process. Sodium tripolyphosphate (STPP) and sodium citrate (SC) were introduced as additives to treat RCF, with concentrations ranging from 0% (reference sample, distilled water only) to 5%. The carbonation process was maintained consistently at 1 hour across all samples. To investigate the influence and effectiveness of STPP and SC on RCF carbonation, comprehensive analyses were performed using various characterization techniques, including X-ray diffraction (XRD), X-ray fluorescence (XRF), thermogravimetric analysis (TGA), and Fourier transform infrared spectroscopy (FT-IR).

The results indicate that STPP and SC can complex calcium ions but differ significantly in complexation strength, influencing their effectiveness in the carbonation process. The calcium complexation ability of STPP was relatively weak, and it could maintain enough concentration of free calcium ions, which could effectively control the formation of calcium carbonate during the carbonation process. In contrast, SC exhibited a stronger chelating affinity, which significantly reduced the availability of free calcium ions and thus inhibited calcium carbonate precipitation; therefore, it did not control the crystallization route of calcium carbonate well. These results suggest that moderate calcium complexation is more beneficial to controlling calcium carbonate crystallinity. Additionally, the findings indicate that wet carbonation inherently favors the formation of stable crystalline phases, such as calcite, making precise control over intermediate or amorphous calcium carbonate phases difficult due to the high availability of water. Overall, these insights highlight the importance of selecting additives and carbonation methods to effectively modulate the carbonate phase and improve the reactivity of recycled concrete materials.

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Inhibition of the short term aging process of bitumen by a binary polymer blend of polyaniline:chitosan

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Keywords: asphalt, foamed asphalt, biopolymer

Introduction

Recycling of construction materials is key aspect of sustainable development. In terms of road construction an increase of reclaimed asphalt pavement (RAP) used in asphalt mix production is particularly important. The major faced problem is aged bitumen in RAP , which has lost its primary properties due to oxidation processes and change of composition. Therefore, both the bitumen binder and the produced asphalt mix become stiffer and more brittle which significantly increases the risk of thermal and fatigue cracking and leading to premature pavement degradation. One way to ensure the required performance of asphalt mixtures is by using modified asphalts. However, application of commercially available modified asphalts requires higher production temperatures and poses a risk of its incompatibility with aged bitumen present in RAP. Further, this may negatively affect thethe performance characteristics of the asphalt mix.
To meet these challenges, a novel method of bitumen modification with application of aging inhibitors that have a carefully designed chemical structure was developed. This approach enables use of higher amount of RAP in newly produced asphalt mixes. Based on the physico-chemical properties (dynamic viscosity, penetration, softening point) of bitumen binders modified with aging inhibitors—and their change after shoty-term aging simulation quantitative indices were determined and optimal processing conditions for bitumen binder modification process were established.

Materials and methods

The experimental plan aimed to determine the optimal homogenization conditions for the bitumen-aging inhibitor composite, including two mixing times (45 minutes, 90 minutes), two conditioning durations (1 hour, 3 hours), and two mixing temperatures (170°C, 150°C). In modyfication process polymer blend composed of a synthetic polymer (polyaniline) and a biopolymer (chitosan) was applied. The obtained bitumen–polymer composites were subjected to short-term aging using the RTFOT method according to PN-EN 12607-1. The following tests were conducted on the resulting samples: softening point (PN-EN 1427), penetration (PN-EN 1426), dynamic viscosity using the Brookfield viscometer (ASTM D 4402) and fatigue durability tests (LAS). Aging indices i.e. PRR (Penetration Retention Ratio), SPI (Softening Point Increacement) and VAI (Viscosity Ageing Index) were subsequently calculated and optimal processing conditions were identified. Moreover, for all analysed bitumen, both before and after ageing, G* values were determined from which rheological ageing indices in the form of CMAI (Complex Modulus Ageing Index) were determined.

Results and discussion

The results analysis clearly indicates possibility of short-term bitumen aging inhibition by bifunctional polymer blend. Compared to the reference bitumen, the most significant changes were observed in penetration values. For unmodified bitumen conditioned at 150°C, the penetration was 59 × 0.1 mm after 1 hour and 56.6 × 0.1 mm after 3 hours. When the conditioning temperature was increased to 170°C, penetration values of 61.0 × 0.1 mm and 64.0 × 0.1 mm were determined, respectively. After RTFOT aging, a significant drop in penetration was observed for each of these samples, ranging from 12.7 × 0.1 mm to 21.3 × 0.1 mm. However, the bitumen modified with the polyaniline:chitosan polymeric blend smaller reduction in penetration, ranging from 3.8 × 0.1 mm to 9.8 × 0.1 mm was observed. Only with 90-

minute mixing at 170°C the hardening of the polymeric blend modified bitumen exceed 10 × 0.1 mm. The penetration results obtained and the PRR values determined from them clearly indicate that the use of a polymer mixture in the form of polyaniline and chitosan effectively inhibits the short-term ageing process. This was also confirmed by the rheological index CMAI.

Conclusion

The investigations clearly show that the polymer blend of polyaniline and chitosan effectively inhibits the short-term ageing process of road bitumen. Its positive effect was observed both from changes in physico-chemical properties, i.e. penetration, softening point and viscosity, and rheological properties, i.e. G*. The research is a first step towards systematically increasing the amount of RAP used in the construction of new and durable road pavements.

Founding:

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Innovative connectors for force transmission in thin-walled façade elements made of Carbon Concrete Composite

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Keywords: Thin-walled façade, carbon concrete, connections, fasteners, force transmission.

Thin-walled façade elements are gaining prominence in the construction industry as a sustainable, resource-conserving, and material-saving alternative to conventional elements made from reinforced concrete. Modern concrete façade elements, such as those made of carbon-reinforced or textile concrete, feature large surface areas and low material consumption, often with thin walls. These delicate, thin-walled elements combine economic and resource-saving benefits for a building's visible envelope. However, challenges include manufacturing, transporting, assembling, and ensuring the safety, reliability, and durability of anchoring solutions for large building elements.

Traditional reinforced concrete façade panels typically need to be constructed with a minimum thickness of 90 mm to 100 mm. In contrast, carbon concrete panels, in terms of load-bearing capacity and serviceability, are adequately dimensioned with just 30 mm. This represents a volume and weight reduction by a factor of 3–4. As a result, the load transfer and anchoring of such elements using conventional methods, e.g., anchor channels or dowels, becomes unfeasible due to their small thickness. These methods depend heavily on thickness for load transmission and calculations, as most models use thickness as the key parameter to predict maximum load capacity and ensure safety. The implementation of a modular, prefabricated construction method, along with the extensive use of lightweight elements made of carbon or textile-reinforced concrete, requires new types of connection elements. Thin-walled components made of carbon-reinforced concrete can be much slimmer than comparable reinforced concrete elements. In addition to the geometric conditions for the connection of such thin-walled carbon-reinforced concrete components, the force transmission in these thin elements poses significant challenges for designers and construction personnel. Combined with the need for simple assembly on-site, these challenges can appear to be insurmountable.

As part of research projects at the Frankfurt University of Applied Sciences (FRA-UAS), in cooperation with the building industry, innovative connection solutions using shape memory alloys (SMA) and filigree steel elements for load transmission were developed. The newly developed connection concepts aim to significantly simplify assembly on the construction site. By using memory steel as an active connection element, mechanical access for connections can be eliminated.

The synergy of laboratory tests enables precise optimization of application parameters. Furthermore, long-term tensile pull-out strength under realistic conditions was evaluated. The specimens were subjected to a permanent tensile load of 4 kN by helical compression springs. Field tests demonstrate the full potential of the deformation process, enabling the installation of façade panels without physical access to the joint, thereby enhancing on-site personnel safety. The compact connection between load-bearing components and façade panels allows for the replacement of individual internal elements without dismantling surrounding façade panels. Furthermore, weathering tests conducted at Frankfurt University of Applied Sciences demonstrate that the selected iron-based shape-memory alloy with a high manganese content exhibits excellent corrosion resistance. This research opens up new development opportunities in multiple disciplines, offering resource and energy savings in the construction industry. By reducing material usage and concrete volume, this innovation contributes significantly to lowering energy consumption in the building sector.

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Insights into the Retardation of Calcium Silicate Hydrate (C-S-H) nucleation and growth by Pb^{2+}

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Keywords: synthetic C-S-H, lead ion, nucleation pathway, retardation, immobilization mechanism

1. Introduction

The immobilization of heavy metals, such as lead (Pb^{2+}), in cementitious systems is critical for sustainable waste management, yet their incorporation often retards cement hydration, delaying construction timelines and compromising early strength. While prior studies attribute this retardation to Pb^{2+}-induced suppression of tricalcium silicate (C_3S) dissolution or coating effects, direct evidence linking Pb^{2+} to calcium silicate hydrate (C-S-H) nucleation—the primary products of cement hydration—remains scarce. Current research predominantly focuses on macroscopic outcomes (e.g., setting time, compressive strength) or final C-S-H structures, neglecting the dynamic interplay between Pb^{2+} and C-S-H nucleation pathways. This study bridges this gap by systematically investigating how Pb^{2+} alters C-S-H nucleation kinetics, precursor evolution, and long-term material properties. The findings advance the fundamental understanding of heavy metal interactions in cement systems while guiding the design of eco-friendly, high-performance waste-incorporated construction materials.

2. Methodology

Synthesis: C(-Pb)-S-H samples with Ca/Si = 1.5 and Pb/Si ratios of 0, 0.2, and 0.5 were synthesized under N_2 atmosphere via a double decomposition method. Solutions of $Ca(NO_3)_2$, Na_2SiO_3, and $Pb(NO_3)_2$ were mixed to initiate nucleation, with aliquots sampled at intervals (30 s–24 h).
Characterization: The nucleation process was monitored using inductively coupled plasma (ICP) analysis, X-ray diffraction (XRD), transmission electron microscopy (TEM), and ^{29}Si nuclear magnetic resonance (^{29}Si NMR). Molecular dynamics simulations employing the CLAYFF force field were conducted to model pre-nucleation clusters in Pb^{2+}-containing and Pb^{2+}-free systems. Additional characterization techniques, including X-ray photoelectron spectroscopy (XPS), nitrogen adsorption (BET), and nanoindentation, were used to evaluate chemical states of Pb^{2+}, pore structures, and micromechanical properties.

3. Results and Discussion

3.1 Pb^{2+}-mediated nucleation Pathways

Stage 1 (Precursor Formation): Pure C-S-H formed 50 nm amorphous spheroids with a petal-like structure. Pb^{2+} reduced precursor size to 30 nm and introduced dense "black spots" ($Ca_xPb_\gamma SiOz \cdot wH_2O$) via Si-O-Pb bonding (XPS/NMR). These spots, enriched in Pb (TEM-EDS), exhibited lower solubility (Ksp ~10^{-20} for $Pb(OH)_2$ vs. 10^{-6} for $Ca(OH)_2$), delaying subsequent stages.

Stage 2 (Transformation): Pure C-S-H transformed to foils within 20 min, while Pb-doped precursors required >40 min. Black spots dissolved slowly, releasing ions for reprecipitation (ICP: $Ca^{2+}/H_2SiO_4^{2-}$ fluctuations in stage 2). Zeta potential measurements confirmed slower ion release from Pb-bearing precursors (-57 mV vs. -60 mV at 8 min).
Stage 3 (Maturation): Pb^{2+} reduced foil crystallinity (XRD: diminished (110)/(200) peaks) but enhanced micromechanical properties. Nanoindentation revealed a 48% increase in elastic modulus (from 18.25 to 30.39 GPa) and 136% higher hardness at Pb/Si = 0.5, attributed to refined pore structures (BET: 231 m^2/g vs. 145.7 m^2/g) and reduced defects.

3.2 Molecular Insights into Retardation

MD simulations revealed Pb^{2+}'s "poisoning" effect: Pb^{2+} bound preferentially to silicate oxygens, forming stable Si-O-Pb complexes that hindered Ca^{2+}-silicate aggregation. Cluster growth rates decreased by 40%, with Pb-bearing systems forming smaller nuclei.

The retardation mechanism arises from the low solubility of $Ca_xPb_ySiO_z{\cdot}wH_2O$ within precursors, which slows ion arrangement. This delays C-S-H foil formation, explaining prolonged cement setting times and reduced early strength. However, Pb^{2+} incorporation enhances long-term mechanical properties by refining microstructure and strengthening interfacial bonds. The study clarifies the dual role of Pb^{2+}: as a retardant during early hydration and a microstructural enhancer in mature cement pastes. These findings provide a framework for optimizing Pb-containing waste utilization in cement, balancing immobilization efficiency with material performance.

4. Conclusion

This study elucidates the dual role of Pb^{2+} in C-S-H nucleation: as a retardant during early hydration and a microstructural enhancer in mature pastes. The formation of low-solubility $Ca_xPb_ySiO_z{\cdot}wH_2O$ in precursors delays dehydration process extending the precursor-to-foil transition by over 20 min. However, Pb^{2+} incorporation strengthens C-S-H via Si-O-Pb bonding, increasing specific surface area and micromechanical properties. These findings resolve longstanding ambiguities about Pb^{2+}'s retardation mechanism while demonstrating its potential to improve long-term material performance. By integrating experimental and computational approaches, the work provides a roadmap for optimizing Pb-containing waste utilization in cement, balancing environmental safety with enhanced durability.

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Investigating the potential of ceramic waste powder as a Pozzolanic Material and Inert cement Filler in Concrete.

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Keywords: Ceramic waste powder, Cement, Ground granulated blast-furnace slag (GGBS), limestone powder and concrete.

ABSTRACT

Concrete microstructure consists of aggregates, hardened cement paste, calcium silicate hydrate (C-S-H) gel, calcium hydroxide (CH), interfacial transition zones, voids, and microcracks. Understanding these components is essential for incorporating cement fillers and supplementary cementitious materials (SCMs) to enhance performance. Fillers, such as limestone powder, are inert and improve concrete density without reacting with the hydration product, CH. SCMs, however, chemically react to form additional C-S-H, enhancing long term strength and durability. Ceramic waste powder (CWP) contains silica (SiO_2) and alumina (Al_2O_3). Thus, it possesses the potential to enable pozzolanic reactions with CH to form C-S-H. However, research on CWP's reactivity is inconclusive. Some studies classify it as an inert filler that only improves durability by filling voids in concrete microstructure but has little strength impact. In contrast, others report pozzolanic activity that improves long-term strength. Given these conflicting findings, further investigation is needed. This study explores CWP's role as a partial replacement for both pozzolanic material (GGBS) and inert filler (limestone powder) in concrete.

The CWP was sourced from renovation wastes, including discarded tiles and sanitary wares. The waste was cleaned, sun-dried, crushed with a jar crusher, and milled into fine powder using a laboratory pulveriser. Figure 1 illustrates the transformation process.

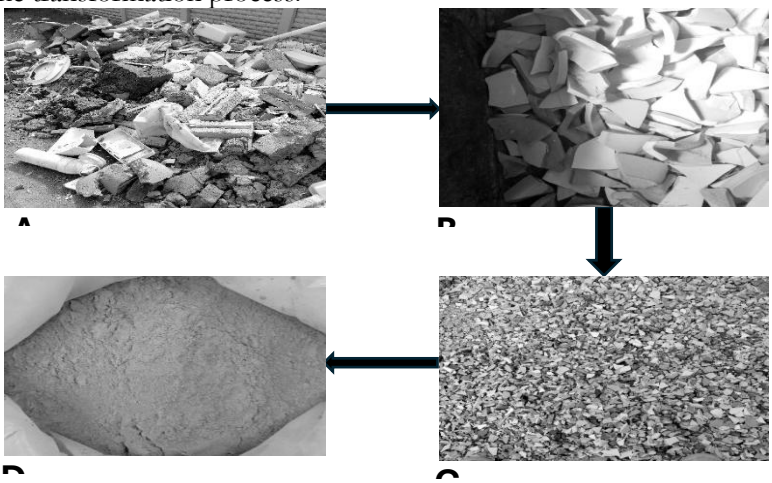

Figure 1: Transformation of ceramic wastes into CWP

Table 1 presents the binder formulations. Two reference mixes were used: 70% PC + 30% GGBS and 90% PC + 10% limestone powder. CWP partially replaced these materials. A 0.55 water-binder ratio was used, targeting a compressive strength of 35–40 MPa.

Table 1: Binder formulations

S/No	Mix label	Binder formation	Percentage Composition of CWP (%)
		Replacement of GGBS with CWP	
1	**M1C**	**70% PC+ 30% GGBS**	**0**
2	M2C	70% PC + 20% GGBS + 10 % CWP	10
3	M3C	70% PC + 10% GGBS + 20% CWP	20
		Replacement of limestone powder with CWP	
4	**M4C**	**90% PC + 10% limestone powder**	**0**
5	M4C	90% PC + 5% Limestone + 5% CWP	5
6	M6C	90% PC + 3% Limestone + 7% CWP	7

The experimental program consists of three phases:

1. **Binder Characterization:** This includes particle size distribution, specific gravity, bulk density, and chemical composition using XRF and SEM-EDS
2. **Fresh Concrete Properties:** Slump tests were conducted to determine the concrete workability.
3. **Hardened Concrete Properties:** Compressive strength tests and splitting tensile strength were conducted at 7, 28, 56 and 90 days. Durability index tests (oxygen permeability, chloride conductivity, water sorptivity), and microstructural analysis (SEM) were also performed.

The results indicate that CWP demonstrates superior pozzolanic behaviour compared to limestone powder. Concrete mixes where CWP replaces limestone powder exhibit higher mechanical properties than their reference mixes. However, in GGBS-based concrete, the highest mechanical properties are observed in the reference mix, with a slight decrease as CWP replaces GGBS.

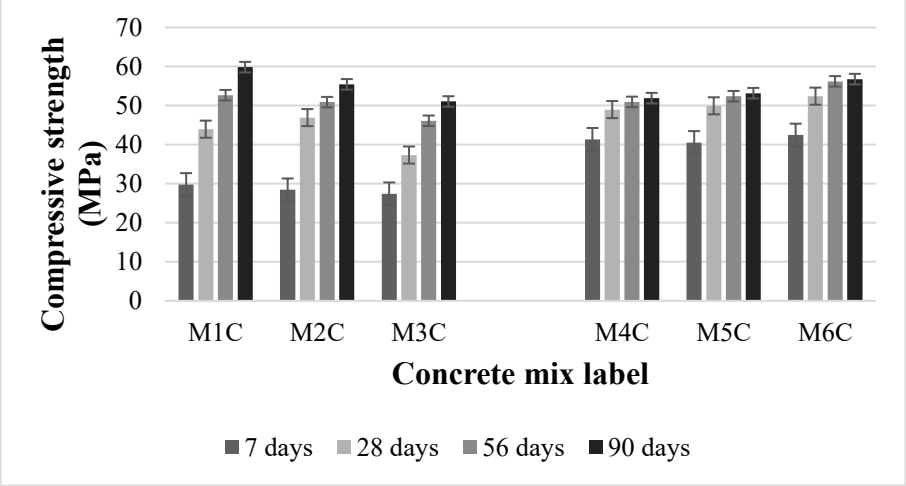

Figure 2: Compressive strength of CWP concrete

Figure 1 shows the compressive strength of CWP concrete. For the GGBS-based mixes (M1C, M2C, and M3C), compressive strength decreases with increasing CWP content, particularly at early ages. At 7 days, M1C achieves the highest strength of 29.79 MPa, while M2C and M3C record 28.43 MPa and 27.41 MPa,

respectively. By 28 days, M1C achieves 43.96 MPa, while M2C slightly surpasses it with 46.93 MPa, showing the beneficial effect of 10% CWP at this age. However, M3C falls behind at 37.34 MPa, indicating that 20% CWP replacement negatively impacts strength. By 90 days, M1C achieves the highest strength of 59.84 MPa, while M2C and M3C reach 55.44 MPa and 51.05 MPa, respectively, showing a clear reduction in long-term strength with higher CWP content. In contrast, the limestone-based mixes (M4C, M5C, and M6C) show consistent improvements in compressive strength with CWP replacement. At 7 days, M6C achieves the highest strength of 42.45 MPa, surpassing M4C (41.35 MPa) and M5C (40.55 MPa). By 28 days, M6C continues to outperform with 52.41 MPa, compared to 49.94 MPa for M5C and 48.98 MPa for M4C. At 56 and 90 days, M6C maintains its superiority, achieving 56.21 MPa and 56.78 MPa, respectively, while M4C lags at 51.90 MPa by 90 days.

In conclusion, CWP enhances compressive strength in limestone-based mixes, especially at higher replacement levels, improving both early and long-term performance. In GGBS-based systems, 10% CWP improves 28-day strength but reduces long-term strength. While CWP outperforms limestone powder, it is not as effective as GGBS. These findings are also supported by microstructural analysis of CWP concrete.

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Investigation of Strength Contribution of Different C-S-H Forms: C-S-H from Glass Powder – Calcium Hydroxide Reaction vs. Cement Hydration

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Keywords: Concrete, Glass, Calcium Silicate Hydrate, Ca/Si ratio, Silicate Polymerisation.

Introduction

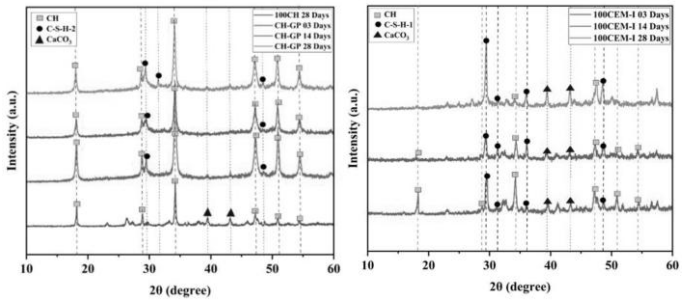
Waste Glass powder (GP) has potential as a partial replacement for cement in concrete. It is expected Silica (SiO2) in GP reacts with Calcium Hydroxide (CH) formed during cement hydration to produce Calcium Silicate Hydrate (C-S-H) (denoted as C-S-H-2 to distinguish it from C-S-H formed during cement hydration which is denoted as C-S-H-1). Despite the expected formation of C-S-H-2, their strength contribution remains poorly understood. If C-S-H-2 forms and contributes to strength same as C-S-H-1, it is unclear why the commonly observed ~20% maximum cement replacement limit with GP. The present study confirms the formation of C-S-H-2 from CH and GP reaction and identifies that lower silicate polymerisation in C-S-H-2 is the reason for its less strength contribution.

Research Methodology

Portland CEM-I cement (52.5 grade), GP (particle size < 75 μm with 70% SiO2), CH powder (particle size < 10 μm with 99% purity) were used in the present study. CH (54%) and GP (46%) was mixed with water (water – (CH+GP) ratio 0.45) to make CH-GP paste, which was cast into 2 cm cubes and water-cured for 3, 14 and 28 days. Reference specimens of CH with water (100CH) and 100% cement paste with water-cement ratio 0.4 (100CEM-I) were also cast into 2 cm cubes. The 100CH specimens were broken upon removal from the mould suggesting its negligible strength. X-ray Diffraction (XRD) was conducted on all specimens to investigate the formation of chemical compounds. C-S-H-2 formation in CH-GP specimens was confirmed using XRD, and the total quantity of C-S-H in CH-GP and 100CEM-I specimens were determined. The 28-day compressive strength test results showed the strength contribution of C-S-H-2 per unit was ~7 times lesser than that of a C-S-H-1 unit. To identify the reason for the lower strength of C-S-H-2, the effects of Ca/Si ratios (using XRD) and silicate polymerisation (using Nuclear Magnetic Resonance (NMR)) in C-S-H were analysed.

Result and Discussion

The XRD results of 100CH specimen at 28 days shows peaks of CH and Calcium Carbonate (due to CH carbonation from atmospheric CO_2) (see Fig. 1). No peaks for C-S-H were detected (since no Silica was available) in 100CH specimen. The peaks of C-S-H-2 in CH-GP and C-S-H-1 in 100CEM-I were observed. The total C-S-H-2 content in CH-GP at 28 days was 54%, while the theoretically predicted amount was 87% (assuming complete CH-GP reaction). The total C-S-H-1 amount at 28 days was 55%, compared to the predicted 60% (assuming complete hydration of C2S and C3S). Although the total amounts of C-S-H-1 and C-S-H-2 in the two types of specimens were similar, the compressive strength of CH-GP specimens at 3, 14, and 28 days was 3.8, 4.9, and 7.8 MPa, respectively, whereas that of 100CEM-I specimens were 32.1, 41.7, and 56.1 MPa at the respective ages. This shows despite having similar quantity of C-S-H in CH-GP and 100CEM-I specimens, the strength contribution of C-S-H-2 was significantly lower than that of C-S-H-1.



(a) **(b)**

To determine the reason for the lower strength of C-S-H-2, the XRD results were analysed to determine the different forms of C-S-H-2 and C-S-H-1 present in the specimens. The results showed the quantities of Tobermorite, Xonotlite and Jennite in C-S-H-2 were similar to that in C-S-H-1 (see Fig. 2). The results suggest different Ca/Si ratio in C-S-H-1 and C-S-H-2 cannot govern the observed reduced strength of C-S-H-2. However, NMR findings highlight the silicate polymerisation in C-S-H-2 showed Q1 structure (79 ppm), while C-S-H-1 showed Q2 structure (85 ppm) at 28 days (see Fig. 3). The difference in strength contribution could be attributed to the difference in silicate polymerisation, as lower polymerisation (Q1) results in fewer cross-linked silicate chains in C-S-H-2, reducing the overall compressive strength. High polymerisation (Q2) promotes the formation of a denser network with stronger silicate bonding, leading to greater compressive strength of C-S-H- 1.

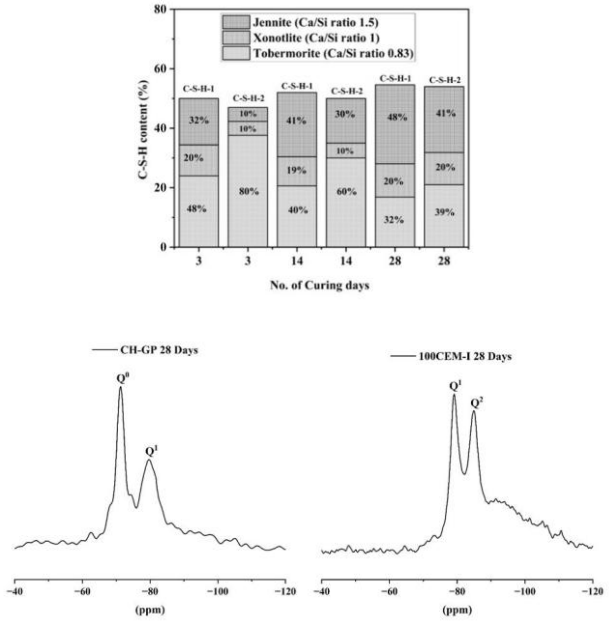


Fig. 3 NMR spectra at 28 days: (a) CH-GP, and (b) 100CEM-I specimens

Conclusions

- This study confirms the formation of C-S-H-2 from CH-GP reaction. Despite the similar amounts of C-S-H-2 and C-S-H-1 were formed, the compressive strength contribution per unit of C-S-H-2 was about seven time lower than C-S-H-1 at 28 days.
- The quantity of different forms of C-S-H in CH-GP specimens was similar to that in 100CEM-1 specimens, suggesting that Ca/Si ratio of C-S-H was unlikely the reason the low strength of C-S-H-2.
- The lower strength contribution per unit of C-S-

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Investigation on Fresh and Hardened Properties of Marble Stone Calcined Clay Cement (MC^3) Using Various Low-Carbon Materials

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Keywords: Limestone calcined clay cement, reactive MgO, red mud, mechanical properties, durability.

As the most widely used building material in the world, cement is not only responsible for a significant portion of global carbon emissions, but also causes high energy consumption in the production process. Therefore, both the amount of CO_2 released and the energy consumption in the production process of cement are among the main factors threating the environmental sustainability. Therefore, researches to develop cementitious systems with a low carbon footprint are becoming increasingly important. The cement industry is focusing on supplementary cementitious materials (SCM) in order to both fulfill the growing demand and minimize environmental impacts. Yet, it is not solely enough to provide environmental aspects; the material produced must also provide satisfactory performance and fulfill the current standards in terms of mechanical properties, workability and durability. In this context, limestone calcined clay cement (LC^3), an advanced ternary binder system that consists of a combination of limestone, calcined clay and gypsum, is emerging as an important alternative in the cement industry. Limestone, calcined clay and gypsum used in LC^3 applications can replace about 50% of the clinker, resulting in a significant reduction of CO_2 emissions during cement production. Instead of limestone, which is used as calcareous material ($CaCO_3$) in LC^3 applications, an alternative system using marble stone dust was designed in this study, which has a remarkable reserve in Türkiye. This system is called marble stone calcined clay cement (MC^3). Türkiye has approximately 40% of the world's marble reserves and a large amount of waste marble dust is generated during marble production and processing. This waste material offers an important recycling opportunity and stands out as a promising material that can contribute to reducing environmental impacts and developing sustainable building materials. This study investigated the use of reactive MgO (r-MgO) and red mud with the aim of providing a more sustainable alternative with lower clinker utilization and better mechanical and durability properties for MC^3 systems. R-MgO has the CO_2 sequestration ability and can contribute to reducing the carbon footprint. On the other hand, red mud is an iron-rich alkaline waste generated during the processing of bauxite ore. The objective of this study is to develop alternative binder systems that reduce clinker utilization to even less than 50% by substituting these two waste materials with cement, both together and separately. Different mixtures containing r-MgO and red mud in the range of 5-20% for each were designed and various tests were carried out on these mixtures. The experimental studies have been conducted to investigate the flow diameter, setting time and workability properties of the MC^3 mixtures in the fresh state. The performance in the hardened state was evaluated in terms of mechanical strength (compressive and flexural strength), physical properties (porosity) and durability aspects (carbonation depth and drying shrinkage). The results obtained were compared with both a reference OPC blend and a MC^3 blend in line with standard LC^3 blends commonly used in the literature. The results revealed that 10% r-MgO substitution improved the mechanical properties, but the consistency was negatively affected when the substitution rate was increased to 20%. It was also observed that the combination of both r-MgO and red mud significantly improved the durability properties.

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Magneto-Responsive Residual Materials for Active Rheology Control in Cement Pastes

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Keywords: Active Rheology Control, Residual Materials, Magneto-Responsive Material, Magnetic Field

Sustainable construction practices increasingly rely on eco-efficient materials to reduce environmental impact while simultaneously enhancing material functionality. A particularly promising path in this field is the approach of Active Rheology Control (ARC), which enables the on-demand modification of rheological behavior through externally applied trigger signals. Among various ARC techniques, the use of an external applied magnetic field in combination with magneto-responsive particles incorporated in the cementitious material has gained significant interest. When subjected to a magnetic field, these magneto-responsive particles form clusters, increasing the material's resistance to flow. This controlled adjustment of rheological properties, induced by an external magnetic stimulus, varies in response to the strength of the applied magnetic field. Such capability is particularly relevant given the growing adoption of automated production processes in the construction industry as well as its potential to mitigate formwork leakage in traditional construction methods.
The influence of magneto-responsive particle properties, particularly their size and saturation magnetization, on the magnetorheological response of cementitious systems has been extensively studied in the last years, with a focus on carbonyl iron powder (CIP) and nano-Fe_3O_4. However, for large-scale applications, magnetic particle selection must meet strict economic, technological and environmental criteria. Given the limitations of these standard materials, it is imperative to identify alternative materials that meet these requirements while maintaining ARC effectiveness. Initial studies in this area have demonstrated the feasibility of incorporating particles from residual materials, such as fly ash and fayalite slag, into cementitious systems for magneto-responsive applications. Building on this foundation, the present study investigates further residual materials with potential magneto-responsive properties for ARC implementation.

Experimental analysis was conducted using vibrating sample magnetometry (VSM) to assess the magnetic properties of these materials. Furthermore, the used materials are analyzed on the basis of their chemical-mineralogical composition and relevant physical-technical and granulometric properties. Oscillatory rheometer tests using a plate-plate geometry and a magneto-rheological device (MRD) were performed to evaluate the influence of particles on the rheological behavior of the cementitious paste. Small amplitude oscillatory shear (SAOS) tests were carried out for 900 seconds with an applied magnetic field strength of up to 0.5 Tesla, with corresponding tests conducted in the absence of a magnetic field for comparison.

The findings indicate that various residual materials, including several types of ash and slag, exhibit promising magneto-responsive characteristics during rheometric testing, making them viable candidates for sustainable ARC applications. However, the magneto-rheological response of cement pastes is not only influenced by the magnetic field strength but also by the concentration, particle size distribution, and composition of the residual materials. These parameters must be carefully optimized to maximize the performance of magneto-responsive cementitious materials in future applications.

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Microstructure and Mechanical Properties of Limestone Calcined Clay Cement (LC^3) with Higher Replacement Ratio.

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Keywords: limestone calcined clay cement, OPC, sustainability, microstructure, mortar, thermal.

A blend of cement (OPC) and limestone calcined clay (LC^2) are expected to be a sustainable alternative to binder in construction industry. LC^2 is recognized for its benefits, including reduced carbon emissions, improved durability compared to OPC, natural abundance of raw materials, and enhanced strength when combined with OPC to form limestone-calcined clay cement (LC^3). Research on the mechanical properties and durability of OPC-LC^2 blend with 30:70 ratio is hardly studied. While environmental benefits of LC^3 are known, data on its strength, workability, and long-term durability are still in its initial stages, corresponding to factors like water-to-binder ratio and superplasticizers. This study explored the effects of varying dosages of water-cement (w/c) ratios and superplasticizers of LC^2-based mixes to address one of the gaps. Both micro- and macro-level analyses will be performed: microstructural evaluations through Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Thermogravimetric Analysis (TGA), while macro-level tests performed were workability and compressive strength. The research provided insights into the optimized mix design for enhancing the performance and sustainability of LC^2-based cementitious materials.

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Optimisation of clinker content and limestone to calcined clay ratio in LC³

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Keywords: clinker content, limestone to calcined clay ratio (LS:CC), degree of hydration, compressive strength, low clinker blends

This study focuses on optimizing the clinker content and the limestone-to-calcined clay (LS:CC) ratio in limestone calcined clay cement (LC³). In applications where high strength is not essential, lower clinker content can be effectively utilized. The investigation was conducted at three clinker levels 30%, 40%, and 50%—while varying the LS:CC ratios at 1:1, 1:2, and 1:3. The optimization process primarily involved evaluating the compressive strength of the different blends. Based on the strength results, a selection of LS:CC ratios were made for further hydration studies to understand the phase assemblage and reaction mechanisms governing the performance of these cement blends. The results indicate that for 30% clinker content, the maximum 28-day compressive strength was achieved at an LS:CC ratio of 1:3. In contrast, for both 40% and 50% clinker contents, the 28-day strength was found to be comparable for LS:CC ratios of 1:2 and 1:3. This similarity in strength suggests that for clinker levels of 40% and 50%, the LS:CC ratio remains within an optimal range when transitioning from 1:2 to 1:3. Based on these findings, further hydration studies were conducted on the 30% clinker blend with LS:CC ratios of 1:1, 1:2, and 1:3, as well as the 50% clinker blend at LS:CC 1:2. X-ray diffraction (XRD) and thermogravimetric analysis (TGA) were performed on hydrated cement paste samples at 1, 3, 7, and 28 days to gain deeper insights into the hydration behaviour. The degree of hydration (DoH) of clinker phases was determined using Rietveld refinement of the XRD data. For 30% clinker content, TGA data revealed that a certain amount of calcium hydroxide (CH) continues to form even at 28 days, facilitating an ongoing pozzolanic reaction with calcined clay. This reaction contributes to the formation of the C-A-S-H phase, supporting strength development at later ages. Among the three LS:CC ratios studied at a clinker content of 30%, the 1:3 blend exhibited the highest clinker hydration, surpassing the hydration levels of the 1:1 and 1:2 blends and showing hydration behaviour comparable to the 50% clinker blend with LS:CC 1:2. Interestingly, the hydration mechanisms of the 30% clinker blend were found to be like those observed in the 50% clinker blend. This indicates that well-optimized low-clinker LC³ formulations can achieve hydration efficiency comparable to higher-clinker blends. This highlights the potential of clinker reduction strategies for sustainable cement production in applications where strength is not the primary requirement.

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Performance evaluation of low clinker multi-blended cements

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Keywords: Slag, Fly ash, Ultrafine SCMs, Heat of hydration, Low clinker

The rise in the demand for infrastructure has a direct impact on cement production, which, in turn, significantly affects the environment. An effective strategy to address the environmental issues associated with cement production is to reduce the clinker factor. Reducing clinker content effectively decreases the CO_2 emissions generated during the clinkerisation process. Supplementary cementitious materials (SCMs) have been extensively used by researchers to achieve this reduction. Commonly utilized SCMs in the cement industry include fly ash, slag, limestone, silica fume etc., owing to their beneficial properties and wide availability. Among these, fly ash and slag have been extensively used over the years due to their positive effects on concrete performance and their ready accessibility across various regions. However, the global transition toward net-zero emissions has led to the gradual shutdown of thermal power plants and steel manufacturing facilities. As a result, the production of fly ash and slag is expected to decline substantially in the coming years. This situation necessitates the search for alternative SCMs and their optimized combinations to maximize their synergistic effects while further reducing clinker consumption.

The present study aims to investigate the performance of multi-blended cement systems by systematically varying the proportions of fly ash and slag while reducing the clinker factor from 45% to 25%. The motivation behind this is to facilitate the increased incorporation of SCMs. Since reducing clinker content typically leads to a decrease in strength due to low reactivity of SCMs, finer cement and a lower water-to-binder ratio was used in this study to counteract this effect and enhance the strength development. Furthermore, utilisation of multiple SCMs in combination with clinker necessitates detailed examination to determine the optimal content and proportion to utilise the full potential of each SCM. To address this concern, a systematic approach has been employed to evaluate the performance of multi-blended binder with reduced clinker content and high proportion of SCMs. To ensure homogenous dispersion of SCMs, a slurry-based approach was adopted, where the SCMs were pre-mixed into a slurry before incorporation into the concrete mix. In this study, concrete samples were cast and subjected to compression at 1,3,7,28 and 90 days of curing. The influence on strength has been examined. The assessment covered both fresh and hardened properties to comprehensively analyse the impact of varying SCMs proportions on workability and strength development. Additionally, a small amount of ultrafine material was introduced to 25% clinker blend to determine whether incorporating a highly reactive SCM could further influence the strength development.

One of the key aspects of this study is the evaluation of hydration kinetics through heat of hydration analysis. Isothermal calorimetry was employed to monitor the thermal evolution associated with cement hydration and to understand SCM hydration as well. the calorimetry studies aimed to establish corelations between the observed heat release peaks, the influence of SCMs (both filler effect and chemical reaction) providing insights into the hydration mechanisms as well as SCM reactivity. This analysis offers critical information regarding contribution of each component in strength gain and durability. Additionally, the influence of ultrafine additions was investigated, as they have the potential to enhance particle packing, optimize particle distribution and refine the microstructure of the hardened cement matrix.

The results of this study contribute to the broader picture of reducing global carbon footprint of cement while still maintaining the structural integrity of concrete. The findings also emphasise the significance of proper proportioning of SCMs to achieve the desired synergy, ensuring that mechanical and durability of the concrete are not compromised despite the reduced clinker content.

Overall, this research highlights the potential of multi-blended cement systems as a viable alternative to the conventional cementitious materials, promoting both ecological benefits and enhanced performance.

Performance of Low-OPC Sulfate-Activated Self-Compacting Concrete Incorporating EAF Slag and 98% Industrial By-Product Content

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Keywords: Sulfate-activated, Self-compacting concrete, Industrial by-products, EAF slag

The integration of industrial by-products in concrete production is increasingly recognized as a strategic solution to mitigate environmental impacts and reduce dependency on natural resources. Among these, ground granulated blast-furnace slag (GGBS), coal fly ash (FA), and steelmaking slag exhibit considerable potential, particularly when activated within sulfate-rich environments. This study explores the development of sulfate-activated self-compacting concrete (SA SCC) comprising a high volume of GGBS and FA, with minor additions of ordinary Portland cement (OPC) and gypsum as activators. Quarry dust (QD) was employed as a fine aggregate, while crushed granite and electric arc furnace (EAF) slag were used as coarse aggregates. The research contributes to expanding the knowledge base on sustainable SCC, addressing a critical gap in the literature concerning sulfate-activated systems with minimal alkali content.

The binder system was meticulously formulated with 72% GGBS and 18% FA, activated by varying combinations of OPC and gypsum (0–10% total). Fourteen SCC mix designs were prepared across two series, Series G (granite) and Series E (EAF slag), and evaluated for fresh, mechanical, dimensional stability, and microstructural properties over a curing period of 270 days. Notably, SCC mixes required only a water-to-binder (w/b) ratio of 0.27 to 0.33 with a constant polycarboxylate-based superplasticiser (SP) dosage of 0.6% to achieve SF2-class workability in accordance with EN 206. Experimental results demonstrated that the fresh properties of SA SCC were significantly enhanced by the inclusion of GGBS and gypsum. Series G mixes exhibited superior flowability compared to Series E due to the smoother surface texture of granite aggregates. In contrast, the EAF slag's rough texture increased internal friction, slightly reducing workability but providing improved bonding at the interfacial transition zone (ITZ). Gypsum replacement of OPC improved the flow diameter, particularly at 6 to 8% gypsum content.

In terms of mechanical performance, SCC containing 4% OPC and 6% gypsum (GPC4WG6 and EPC4WG6) achieved optimal compressive and flexural strength at all curing ages. The compressive strength of SA SCC steadily increased from 7 to 270 days, indicating a prolonged pozzolanic reaction characteristic of GGBS and FA systems. Notably, EPC2WG8 outperformed all other mixes at 270 days, highlighting the potential of EAF slag to enhance long-term performance due to its internal curing mechanism facilitated by porous microstructures. Flexural strength trends aligned with compressive results, with GPC4WG6 and EPC4WG6 again showing peak performance. Microscopic analysis using SEM-EDX at 7 and 182 days revealed that strength development in SA SCC was governed more by dense particle packing and C-A-S-H or C-S-H gel formation around GGBS and FA particles than by a continuous matrix of hydration products. This was especially evident in mixes with low OPC content, where the presence of ettringite and unreacted particles supported a rigid yet discrete structural framework.

Overall, the findings suggest that a high-volume GGBS and FA system activated with minimal OPC and gypsum is a viable, sustainable alternative to OPC-based SCC. The formulated SA SCC not only satisfies fresh and hardened performance criteria but also leverages industrial by-products to reduce carbon emissions, conserve natural resources, and promote circular economy principles. These outcomes are significant in light of Malaysia's Green Technology Master Plan (2017 to 2030), which emphasizes sustainable infrastructure development and waste valorisation.

In conclusion, this study demonstrates that sulfate-activated binder systems can achieve excellent self-consolidating behavior, robust mechanical performance, and enhanced durability using up to 98% industrial by-products by dry weight. This validates their suitability for structural concrete applications and provides a novel pathway for sustainable construction practices.

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Polycarboxylate superplasticizer with narrow chemical composition distribution synthesized via optimal monomer feeding profile

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Keywords: Polycarboxylate superplasticizer, chemical composition distribution, optimal feed profile.

Superplasticizers can significantly improve concrete workability, even with relatively low water-to-cement ratios, thus have been widely applicated in cement industry. Polycarboxylate superplasticizers (PCEs) exhibit superior performance due to their lower dosages, enhanced retention properties, and stronger dispersion abilities. Nowadays, most PCEs are synthesized via batch free radical polymerization which is leading to a broad composition distribution of polymerization products, making it challenging to establish a direct structure-property relationship and sometimes leading to conflicting conclusions. Some controlled/living free radical polymerization techniques have been explored to address this situation, such as reversible-addition fragmentation chain transfer (RAFT) polymerization. However, they may introduce undesirable substances or reduce the molecular weight of the PCEs. In this study, chemical composition distribution can be managed simply by applying calculated optimal monomer addition profiles leading to narrow chemical composition distributions (CCD).

PCEs are copolymers of carboxylic acid-containing monomers and macromonomers with long ethylene oxide side chains. Acid group-containing monomers, usually methylene acrylate acid (MAA) or arylate acid (AA), can enhance the anchoring of the PCE to cement particles, while macromonomers contribute to the steric stabilization of PCEs. The average sequence lengths of the two monomers in the copolymers will be influenced by reactivity ratios and monomer concentrations during polymerization. The monomer with the higher reactivity ratio is consumed more rapidly during the early stages, resulting in a higher molar fraction of that monomer in the beginning of polymerization. Afterwards, towards high conversion, the slower monomer become more incorporated, this phenomena is called composition drift (CD). As the typical growth time of a single polymer chain is in the order of less than a second, this composition drift does not result in block or gradient copolymers but instead to copolymers with a broad CCD. Most likely, heterogeneous copolymers exhibit suboptimal properties as superplasticizers, because only a portion possesses optimal properties. Optimal monomer feeding can prevent CD. Monomer addition profiles as predicted by TRImonomeric Seeded Emulsion Polymerization Simulation(TRISEPS) or the OMAP Excel sheet will be used to keep the balance to achieve a narrow chemical composition distribution of PCEs. Obtaining different CCDs then makes it possible to establish unperturbed structure property relations. Also controlled mixture of narrow CCD copolymers can now be tested.

First, by utilizing the existing software CONTOUR, we can accurately determine relevant reactivity ratios for PCEs synthesis. It is known that these reactivity ratios depend on pH, concentration of the PCE and the choice of monomers. Subsequently, utilizing TRISEPS or OMAP, we can predict monomer addition profiles to obtain homogenous PCEs.

The aims of this study are to (1) produce more efficient PCEs with narrow chemical composition distribution using a semi-batch process; (2) explore the effects of side chain density, side chain length, and main chain sequence lengths to establish direct structure-property relationships for PCEs.

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Potential Applications of Mechanically Recycled Wind Turbine Blades in Concrete

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Keywords: Recycled Glass Fibre-Reinforced Plastic, Fibre-Reinforced Concrete, Sustainable Construction Materials

With the increasing emphasis on sustainable construction materials, the management of end-of-life wind turbine blades (WTBs) presents a pressing challenge. These blades, composed primarily of glass fibre-reinforced polymers (GFRP), are difficult to recycle due to their thermoset matrix. Conventional disposal methods such as landfilling and incineration are environmentally harmful and inefficient. This study investigates the feasibility of integrating mechanically recycled glass fibre-reinforced plastic (rGFRP) into concrete and mortar applications, assessing its mechanical performance and durability. By reusing WTBs in construction materials, this research aims to contribute to the circular economy and reduce the environmental impact of decommissioned wind turbine blades.

To assess the feasibility of using mechanically recycled wind turbine blades in concrete, this study followed a structured experimental approach. The research began with the mechanical processing of wind turbine blade-derived rGFRP, ensuring it was reduced to controlled particle sizes ranging from 0 to 60 mm. These recycled fibres were then further refined to achieve an average fibre length of approximately 5 mm (Figure 1(a)), promoting uniform dispersion in the cementitious matrix and contributing to early shrinkage reduction.

Thermogravimetric Analysis (TGA) and Scanning Electron Microscopy (SEM) were conducted on the fibres to classify the material and assess fibre quality. Since the glass used for reinforcing fibres is E-glass, which is not durable in an alkaline environment, the focus was placed on assessing its early shrinkage impact, as the addition of fibres is intended to mitigate shrinkage cracking. Following material preparation, concrete specimens were designed with varying rGFRP contents. Fresh concrete properties, including compressive strength, were evaluated following standard procedures, while early shrinkage was analyzed using a specialized wind tunnel test. The wind tunnel tests examined the effect of recycled GFRP on shrinkage crack formation. Concrete mixtures with fibre contents of 0–0.9% were tested on slabs (1600 × 600 × 80 mm) restrained by a steel frame to simulate large-area slab behavior. The tests were conducted over a duration of 7 hours under a transparent wind tunnel with a wind speed of ~5 m/s. Crack formation was assessed by counting cracks, measuring their dimensions, and calculating opening areas. Additionally, evaporation rate, temperature, and humidity were monitored to evaluate their impact on plastic shrinkage cracking.

As illustrated in Figure 1(b), some fibre cross-sections exhibited longitudinal cracks, potentially reducing their diameter to below 3 micrometres. These cracks likely resulted from mechanical processing, indicating stress-induced fibre degradation. This reduction in diameter increases the risk of forming WHO-classified fibres, which may pose health concerns and affect fibre performance. TGA revealed that the inorganic fraction of the material accounted for approximately 56% of its total mass.

Concrete spread was assessed at 5, 30, and 60 minutes, revealing no linear correlation with fibre content, suggesting inhomogeneous distribution. Higher fibre content reduced spread due to increased cohesion and viscosity, while regression analysis indicated that homogeneous fibre distribution further lowers spread. The inclusion of shredded GFRP, containing fibres and fine thermoset aggregates, restricted flowability, increased internal friction, and reduced segregation, leading to lower spread values, emphasizing the need to balance fibre reinforcement benefits with workability for effective placement and compaction.

For a fibre content of 0.5 vol.%, the compressive strength after 28 days increased by 7%, as illustrated in Figure 1(b). In general, all samples containing rGFRP exhibited higher compressive strength compared to the reference after 28 days, demonstrating that the incorporation of rGFRP does not have a negative impact on mechanical properties.
Due to the composition of the fibres, which consist of E-glass and are known to lack durability in an alkaline environment, no bending tests were conducted. For future research, it is recommended to extend the testing period to evaluate the long-term effectiveness of the reinforcement, as its mechanical contribution may diminish over time.

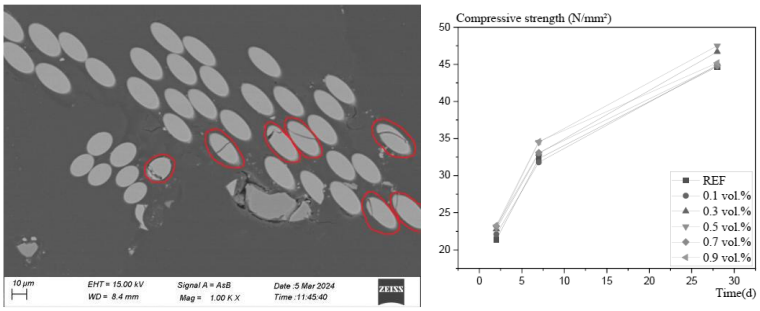

Figure 1: (a) SEM images of fibre intersections < 0.5 mm, (b) Compressive strength after 2,7 and 28d

The wind tunnel tests showed that while most samples with rGFRP exhibited slightly increased shrinkage cracking compared to the reference, the differences were minor. The exception was the sample with 0.5 vol.% fibres, which demonstrated a slight reduction in total shrinkage surface, suggesting a potential benefit in mitigating shrinkage. The low water absorption of rGFRP led to some excess free water in the mix, contributing to slightly greater drying shrinkage in most cases.
This study demonstrates the potential for integrating mechanically recycled GFRP from wind turbine blades into concrete, contributing to sustainable construction practices and the circular economy. The experimental results indicate that rGFRP does not negatively impact the compressive strength of concrete, with a fibre content of 0.5 vol.% even leading to a 7% increase after 28 days. However, higher fibre contents slightly increased shrinkage cracking, except for the 0.5 vol.% sample, which showed a reduction in total shrinkage surface. The challenges identified, such as inhomogeneous fibre distribution, increased viscosity, and the weak durability of E-glass in alkaline environments, highlight the need for further optimization. Future research should focus on improving fibre dispersion and assessing long-term durability. Furthermore, the separation of plastic and E-glass in mechanically recycled wind turbine blades would be highly beneficial for their reuse in concrete applications. Currently, the variation in plastics used by different manufacturers presents a significant challenge for predictable and reliable concrete performance, as these materials interact differently within the cementitious matrix. A systematic separation process could substantially improve the reproducibility of results and allow for more precise optimization of concrete mixtures. Furthermore, finely ground E-glass could be utilized as a pozzolanic additive, contributing to the strength development of the cement matrix and enhancing the overall potential of recycled materials in sustainable construction.

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Pretreatment of supplementary cementitious materials: Effect on water demand and hydration kinetics

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Keywords: slag, fly ash, calcined clay, surface modification, hydration

Abstract
Supplementary cementitious materials (SCMs) such as fly ash, calcined clay, silica fume, and ground granulated blast furnace slag (GGBFS) have been utilized for producing blended cements to lower the clinker proportions and the associated carbon footprint of the construction industry. These materials not only, lower carbon emissions, but also contribute significantly to additional hydrate formation as well as enhance the reactivity of the clinker through filler effect. While additional hydrate formation, or (more commonly) the chemical effect of SCMs is associated with their reactivity in alkaline cement pore solution and the availability of clinker hydration products such as portlandite, the initial filler effect is related to the specific surface area (SSA) of these SCMs and the availability of sites for nucleation of hydrates. The increase in surface area, even though enhances the early rate of hydration, it also affects the workability of cement and concrete produced using these fine SCMs. On the other hand, the slower reactivity of SCMs and the substitution of clinker often result in lower early strength. This study intends to investigate the influence of pretreatment of SCMs using zinc oxide (ZnO) and tri-ethanol amine (TEA) on the surface modification, water demand and hydration kinetics of the corresponding blended cements.
The pretreatment of SCMs involved preparation of slurries using the chemicals, followed by drying and grinding. For this purpose. three SCMs, viz. fly ash (FA), calcined clay (CC) and slag (GGBFS) were used. To prepare the water-chemical solutions, the amount of the chemicals was chosen as 0.05% of ZnO and 0.2% of TEA by weight of the SCMs, while the amount of mixing water was decided such that the resulting slurry didn't overflow from the mixer. The chemical solution was first mixed at low speed (140 rpm) for 5 minutes in a mortar mixer. Subsequently, 1800 g of an SCM was added to the solution and the slurry was mixed for another 15 minutes at high speed (285 rpm). Afterwards, the slurry was poured onto a flat plate and stored in a temperature-controlled room at 27°C. Once visibly dry, the samples were dried in an ambient air oven at 80°C for 24 hours. Subsequently, the treated SCM samples were ground in a laboratory ball mill to match the particle size of the corresponding untreated SCMs (as much as possible), and the specific surface area of these samples were compared using the BET method. Finally, calcined clay was used to prepare Limestone Calcined Clay Cement (LC^3), fly ash was utilized in making Portland Pozzolana Cement (PPC) and the slag samples were blended to produce Portland Slag Cement (PSC). The water demand of the cement blends was evaluated by mini-slump spread test. Isothermal calorimetry was performed on the cement samples at a water-binder (w/b) ratio of 0.40 to assess the effect of pretreatment on the hydration kinetics.
The effect of pretreatment on the required grinding energy was evaluated using a laser diffraction particle size analyzer. It was observed that the D_{10}, D_{50} and D_{90} values of calcined clay were unaffected by the pretreatement and the fineness values could be matched with that of the untreated sample with 200 rotations in the ball mill. On the other hand, the D_{10} and D_{50} values decreased significantly in fly ash and slag samples at just 50 and 100 ball mill rotations, indicating an increment in the finer proportions. On the

contrary, the BET SSA measurements indicated a subtle increase in both ZnO and TEA treated calcined clay samples. The ZnO treatment resulted in a marginal enhancement while TEA treatment caused a small decrease in the SSA of fly ash and slag samples from the corresponding untreated samples. However, the TEA treated slag and fly ash cement blends depicted a higher water demand, while LC^3 made with ZnO as well as TEA showed a marked reduction in the water requirement. Results from hydration kinetics suggested that the increase in fineness and SSA caused by ZnO resulted in a reduction in the induction period and an increment in the peak heats in all the blends. However, TEA treatment caused significant acceleration in LC^3 with hints of 'undersulphation' while it resulted in an excessive retardation in the PSC blend. The anomalous behaviour with TEA treatment warrants a further detailed investigation.

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Production of green asphalt mixtures in terms of sustainable development of road engineering

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Keywords: low-emission technologies, life-cycle extension, bitumen ageing, oxidation, road destruction.

Modern civil engineering is increasingly focused on meeting sustainability requirements, particularly by developing low-emission, environmentally friendly technologies. A significant challenge in this field is the production of asphalt mixtures, which typically require high temperatures (160-180ºC) along with organic bitumen binders. This process can release hazardous gas compounds into the atmosphere, including SO2, NOx, CO, and VOCs. To comply with the latest emissions regulations, it is essential to reduce the production temperature of asphalt mixtures. This reduction can be achieved using bitumen foaming technology. Currently, two bitumen foaming methods have been developed: the direct injection of water into hot bitumen binders and the use of water carriers made from porous materials. In these processes, water is evaporated to create an asphalt foam, which allows the mineral aggregate to be coated effectively at lower temperatures. Additionally, sustainable road construction aims to extend the lifespan of pavements by applying ageing inhibitors to bitumen binders. Bitumen, being an organic material, is susceptible to deteriorating external factors like high temperatures and UV radiation. These factors lead to chemical changes in bitumen binders, primarily through the oxidation of carbon and sulfur atoms. The effects alter the physical and chemical properties of bitumen, leading to the formation of cavities and cracks in the road pavement structure. These phenomena are referred to as ageing processes, which occur throughout the life cycle of road pavements, from the production of the asphalt mix (short-term ageing, STA) to its service life (long-term ageing, LTA).

In addressing the challenges associated with sustainable road construction, specifically the need to reduce the production temperature of mineral-asphalt mixtures and extend their service life this research focused on the design and synthesis of modern zeolite-oxide binary additives. The primary objective of these additives is to facilitate the foaming of the bitumen binder while also mitigating its destructive ageing processes. For the synthesis of composites intended for the foaming of the bitumen binder, synthetic zeolites, specifically of the NaX and NaP1 framework types, were utilised. These zeolites were produced through the hydrothermal conversion of fly ash, which is a byproduct of the energy industry. In addition, metal oxide nanoparticles, namely CuO, ZnO, and TiO_2, were incorporated as agents to impede the destructive ageing processes. These nanoparticles were introduced into the porous zeolite structures at a loading of 5% w/w through precipitation methods. Ultimately, six distinct zeolite-oxide composites were developed: NaX_CuO, NaP1_CuO, NaX_ZnO, NaP1_ZnO, NaX_TiO_2, and NaP1_TiO_2. These composites were subsequently evaluated for their foaming efficacy and their capacity to inhibit both short-term and long-term ageing of the bitumen binder.

The efficiency of the 35/50 bitumen foaming process was analyzed by investigating the expansion coefficient (EC) and the half-life of the foaming effect (t1/2) for three different composite contents: 2% w/w, 4% w/w, and 6% w/w. The expansion coefficient (EC) quantifies the increase in volume of the binder, while the half-life (t1/2) indicates the duration that the produced foam remains effective. The results showed that as the amount of composite used increased, the efficiency of the foaming effect also improved. Specifically, a nearly threefold increase in bitumen volume was observed when the NaX_CuO and NaP1_CuO composites were added at a 6% concentration. The NaX_TiO_2 and NaP1_TiO_2 composites

produced slightly higher EC values. However, the highest EC values were obtained with composites containing ZnO nanoparticles. It is important to note that although the EC increased, there was a corresponding decrease in the t1/2 value of the foaming process.

The process of technological and service ageing of bitumen was investigated by changes in physical properties such as penetration, softening point, and dynamic viscosity. This was accomplished by calculating ageing indices: the Softening Point Increment (SPI) and the Viscosity Aging Index (VAI). The ageing simulation followed the current standards for bitumen that had been foamed with 4% and 6% w/w of various composites: NaX_CuO, NaP1_CuO, NaX_ZnO, NaP1_ZnO, NaX_TiO_2, and NaP1_TiO_2. The SPI values, derived from softening points determined according to the PN-EN 1427 standard, showed that the anti-ageing effects of the tested two-component composites were only observed with the 6% additive. This effect was more pronounced during service ageing, where foaming the bitumen with the NaX_ZnO composite resulted in a reduction of SPI values by up to 5ºC. Similar trends were observed with the VAI calculated using dynamic viscosity, measured according to the PN-EN 13302 standard. In this instance, the VAI value after long-term ageing of bitumen foamed with the NaP1_ZnO composite decreased by nearly 50% compared to the reference bitumen. Additionally, the investigation focused on the chemical changes occurring during the ageing process of bitumen binders. To achieve this, the Fourier Transform Infrared Spectroscopy (FTIR) spectra of foamed and aged bitumen were analyzed, along with the carbonyl and sulfoxide indices that quantify the oxidation reactions of carbon and sulfur atoms present in bitumen-building hydrocarbons. The results indicate that zeolite-oxide composites containing 5% nanoparticles inhibit oxidation reactions of C and S atoms more effectively during the production of asphalt mixtures than when the mixtures are applied to road pavements. Notably, for the NaX_ZnO composite, there was an observed six-fold decrease in carbonyl and sulfoxide index values.

In conclusion, the study demonstrated that zeolite-oxide bicomponent composites can be successfully used in the foaming of bitumen binders and effectively inhibit destructive ageing processes. This indicates that their commercial application will enable the production of environmentally friendly asphalt mixtures that will fully meet the requirements of sustainable development.

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Reactivity of SCMs in Multi-Constituent Blended Cements: Exploring Interaction Mechanisms

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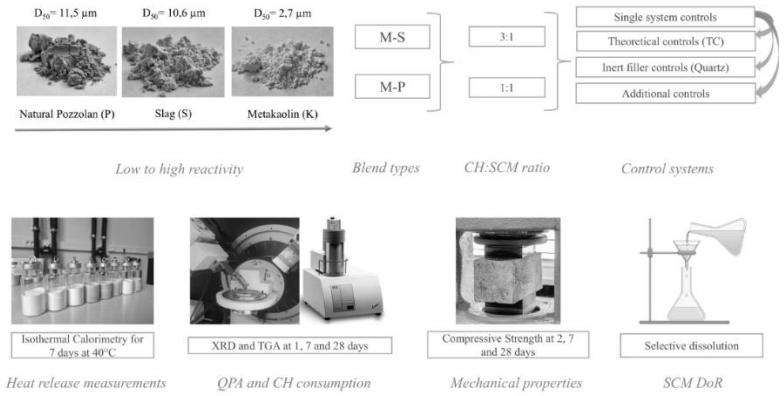
Keywords: Reactivity, SCMs, Interaction, Competition, Degree of Reaction (DoR).

Multi-constituent blended cements have gained significant attention as an effective pathway to substitute Portland clinker with supplementary cementitious materials (SCMs) and reduce CO_2 emissions from the cement production. Previous studies have documented the effect of multi-constituent blending on the hydration of clinker phases and its influence on the hydrate assemblages. Extensive research has explored SCM-clinker interactions, limestone-cement interactions and limestone-SCM interactions. However, SCM-to-SCM interactions remain largely unexplored, in particular in terms of the reactivity of the SCMs. To address this gap, this study aims to provide new insights in the interactions between SCM reaction dynamics at 40°C in lime-based model pastes.

Binary blends of metakaolin (M) – slag (S) (high and medium reactive SCMs) and metakaolin (M) – natural pozzolan (P) (high and low reactive SCMs) were prepared with calcium hydroxide (CH) to SCM ratios of 3:1 (high CH availability) and 1:1 (limited CH availability). Additionally, theoretical controls (TC) were made by averaging the results from single SCM testing under identical conditions, for comparative analysis. A multi-technique approach was applied to quantitatively assess the impact of interactions on SCM reaction rates and reaction product formation. The interaction mechanism was investigated using a combination of techniques from calorimetry to measure the heat release up to 7 days, over thermogravimetric analysis (TGA) to measure CH consumption, to quantitative X-ray diffraction (XRD) combined with Rietveld analysis (external standard method) for hydrate identification and quantitative phase analysis (QPA). Compressive strength testing on lime mortars was made for performance assessment. To determine the degree of reaction (DoR) of each individual SCM in the different systems, a new approach combining selective dissolution with heat release measurements was used.

Results showed that, in high CH availability systems (3:1 CH:SCM mass ratio), the heat release in blended SCM systems closely matched the theoretical controls, indicating independent, unconstrained SCM reactions. However, under limited CH availability (1:1 CH:SCM mass ratio), blended systems released significantly more heat compared to their corresponding controls, suggesting a competition dynamic. Moreover, blended systems at 1:1 consumed more CH than their TCs. In the M-S and M-P systems, M acted as a highly competitive reactant, as it is the most reactive SCM in this study, intensively consuming CH and reducing CH availability for the less reactive SCM. This is mirrored in the measured DoR of the individual SCMs where the competitive dynamic increased MK's DoR while partially supressing the reaction of the less reactive SCM which can be considered to act as a "reactive filler". The DoR of the less reactive SCM in the blend was lower than expected comparing with the single SCM systems. Despite the competition, the less reactive SCM still contributed to hydration, demonstrating that competition, rather than complete inhibition, governs the interaction dynamics between SCMs. Ultimately, this competition

dynamic increased the overall system DoR, driving more extensive hydration as seen in QPA and higher compressive strength than in single systems. This work introduces the concept of the reactive filler effect in binary SCM blended systems and provides new insights into the competition dynamic between blended SCMs which results in an overall synergetic effect.



Schematic diagram of the experimental workflow followed to investigate the interaction dynamic of SCMs in binary blended systems.

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Rice Husk Ash in Concrete: A Theoretical Investigation Towards Maximising the Cement Replacement Percentage

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Keywords: Concrete, Calcium Silicate Hydrate, Rice Husk ash, Reactive Silica, SCM

Introduction: The increasing scarcity of conventional supplementary cementitious materials (SCMs) such as ground granulated blast-furnace slag (GGBS) and fly ash has intensified the demand for sustainable alternatives, particularly bio-based SCMs. Among them, Rice Husk Ash (RHA), which has emerged as a viable SCM option due to its high silica content (>75%) and the ability to form Calcium-Silicate-Hydrate (C-S-H) from the chemical reaction with Portlandite ($Ca(OH)_2$) in concrete mixes. However, despite ongoing research, the widespread use of RHA in cementitious systems remains limited due to lack of scientific understanding. Although the total silica content in RHA is typically reported in the range of 75–90%, not all this silica contributes to the chemical reaction. Silica in RHA exists in amorphous and crystalline forms, with only the amorphous portion generally considered reactive. Studies suggest that the reactive silica fraction, which is often measured as amorphous/soluble silica, can be low as 60% compared to total silica, yet there is limited understanding of the reactivity of RHA in concrete. Experimental studies commonly report that 10–25% RHA replacement achieves 28-day compressive strength comparable to reference concrete, although findings vary widely. This abstract presents selected findings from an ongoing major research investigation which explores the feasibility of high cement replacement levels (>40%) using RHA without compromising the properties of concrete. A theoretical approach based on C-S-H formation, considering varying reactive silica contents, is compared against experimental compressive strength data. Results show discrepancy between total and reactive silica, as well as mismatches between the predicted C-S-H and observed compressive strength. The results suggest the need for scientific understanding of RHA-blended cementitious systems.

Methodology: Theoretical calculations based on mole concept theory were conducted to determine the expected total C-S-H quantity in cement-only and RHA-cement systems. The amount of C-S-H from cement hydration (C-S-$H_{(CEM\ I)}$) and resulting $Ca(OH)_2$ were calculated based on the complete hydration of C_3S and C_2S (Equation 1 and 2). In RHA-cement systems, silica from RHA reacts with resulting $Ca(OH)_2$ from cement hydration to form C-S-$H_{(RHA)}$ (Equation 3). As for the reactive silica percentage, a range of 50-90% was considered to investigate its effects on total C-S-H formation.

$$\underset{C_3S}{2[(CaO)_3(SiO_2)]} + 6H_2O \rightarrow \underset{\text{C-S-H }(CEM\ I)}{(CaO)_3(SiO_2)_2(H_2O)_3} + \underset{CH}{3[Ca(OH)_2]} \quad \text{Eq.1}$$

$$\underset{C_2S}{2[(CaO)_2(SiO_2)]} + 4H_2O \rightarrow \underset{\text{C-S-H }(CEM\ I)}{(CaO)_3(SiO_2)_2(H_2O)_3} + \underset{CH}{Ca(OH)_2} \quad \text{Eq.2}$$

$$\underset{CH}{3[Ca(OH)_2]} + \underset{S}{2SiO_2} + H_2O \rightarrow \underset{\text{C-S-H }(RHA)}{[(CaO)_3(SiO_2)_2(H_2O)_4]} \quad \text{Eq.3}$$

Results: Figure 1 illustrates the theoretical C-S-H formation against cement replacement percentage for varying reactive silica levels considered in this study.

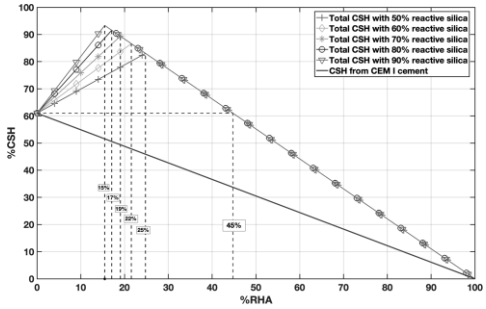

Figure 1: Variation of theoretically calculated total C-S-H for various percentages of reactive silica (50-90%)

When reactive silica is in the range of 70–90%, the maximum RHA replacement falls between 15–20%, aligning with experimental results for RHA containing 75–90% total silica. As reactive silica decreases, higher replacement levels become theoretically possible, assuming adequate C-S-H formation. The analysis suggests that even at 50% reactive silica, a 25% replacement can be achieved, though such levels are only reported experimentally for RHA with ≥75% total silica. This highlights the importance of distinguishing between total and reactive silica. Furthermore, at 45% cement replacement, the total C-S-H content is equivalent to that of control mixes (0% RHA) across all reactive silica levels, indicating the feasibility of up to 45% RHA use without compromising total C-S-H formation.

Figure 2 compares the theoretical C-S-H trend at 60% reactive silica with experimental 28-day compressive strength data from published studies. The 60% level is selected based on literature reports suggesting that amorphous or soluble silica in RHA can be as low as 60%, despite total silica being 75–90%

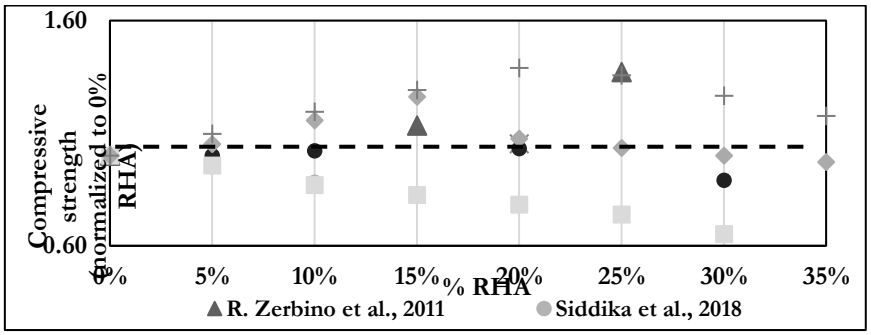

Figure 2: Variation of normalised theoretically calculated total C-S-H and the compressive strength at varying % RHA at 28 days

While some experimental data align with the theoretical trend, especially for 15–25% RHA replacement, compressive strengths generally fall below reference concrete at 20–30%. This gap suggests two factors: (1) not all C-S-H contributes equally to strength due to potential differences in quality, and (2) actual reactive silica in experiments may be lower than assumed.

Conclusions:

- Theoretical analysis suggests that RHA replacement up to 45% is possible without compromising total C-S-H formation.
- A clear gap exists between total and reactive silica; while total silica is often 75–90%, reactive silica can go lower than that.
- Reported findings on strength do not directly correlate with C-S-H quantity, likely due to differences in quality or structure between primary and secondary C-S-H.
- Further research is needed to link particle size, specific surface area, and reactive silica to hydration products via microstructural analysis for optimizing RHA-blended systems.

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Rigidity percolation threshold in cement pastes: A comparative analysis with theoretical percolation threshold and stability volume fraction

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Keywords: bleeding, cement paste, percolation threshold, superplasticizer adsorption, yield stress

The percolation threshold, defined as the minimum solid concentration required to form a connected particle network, is fundamentally linked to the balance between attractive colloidal forces and Brownian motion. Such parameter plays a significant role in influencing the yield stress of cementitious materials. However, despite its importance, there is lack of standard test methods or validated theoretical/empirical models for the assessment of percolation threshold in cement-based materials. In practice, it is often determined through the regression analysis of yield stress data, though this approach yields values with considerable variability and unclear dominant governing forces.

This study aims to investigate the validity and physical implications of the fitted percolation threshold derived from the rheological measurements of cement pastes. For this, Cement pastes were prepared with delayed addition of superplasticizers, so that limited superplasticizers would be intercalated into the layered hydration products, modifying the specific surface area created in the first few minutes of hydration. Moreover, both adsorption and rheological measurements were conducted within the induction period to minimize the increase in solid volume fraction. Two typical yield stress models, the analytical approach (Yodel) and the empirical model (Modified shifting factor, MSF), were used in the regression analysis of yield stress to cross-validate the accuracy of the obtained percolation threshold values. The contributions of Brownian motion, colloidal interactions, and gravity to the fitted percolation threshold were evaluated to reveal its microscopic physical meaning. Additionally, the relationship between fitted and theoretical percolation thresholds was established. The correlation between fitted percolation threshold and bleeding of fresh cement pastes was then examined to uncover its macroscopic physical implication. Based on experimental findings and theoretical analyses, the following conclusions can be drawn:

The fitted percolation threshold derived from yield stress regressions corresponds to the rigidity percolation threshold instead of the theoretical percolation threshold. The rigidity percolation threshold is determined by the interplay between colloidal forces and dominant separating force (gravity or Brownian force), associated to the formation of a mechanically stable interaction network.

The rigidity percolation threshold of cement pastes exhibits a linear relation to the frequency of polymer devoid contacts. The value of this parameter in absence of polymer is influenced by the particle characteristics, while its value at full surface coverage is governed by both particle properties and adsorbed layer thickness of PCEs.

For cement pastes, the effective gravity is the dominant separating force. The rigidity percolation threshold is far greater than the theoretical percolation threshold. In this case, the theoretical percolation threshold

can be determined by a power-law function of rigidity percolation threshold, with the exponent related to the gravitational Péclet number.

For pastes incorporating large amounts of fine particles, where Brownian motion dominates over gravity, the rigidity percolation threshold coincides with the theoretical percolation threshold.

In cement pastes, the rigidity percolation threshold is directly related to the bleeding behaviour, corresponding to the stability volume fraction. When the solid volume fraction exceeds the rigidity percolation threshold, Van der Waals attractive force surpasses gravity, forming a stable connected network of cement grains. Therefore, the suspension remains homogeneous. Conversely, when the solid volume fraction falls below the rigidity percolation threshold, gravity overcomes Van der Waals attractive force, instantaneously destroying the internal particle network. Thus, the bleeding can be observed in the next few hours before setting.

The findings of this study hold significant values in investigating the flowability and stability of cementitious materials, particularly those incorporating large numbers of fine alternative powders for enhanced sustainability.

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Screening the potential for substituting clay soil with sewage sludge ash in fired and unfired bricks

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Keywords: secondary resources, unfired bricks, fired bricks, recycling

Sewage sludge has traditionally been used as fertilizer due to a high content of nutrients such as P. However, sewage sludge is increasingly being incinerated at wastewater treatment plants due to failure to comply with regulation of heavy metal content in the sewage sludge for fertilizer use. The resulting sewage sludge ash (SSA) contains high P concentrations (5-15 %) P, but is also rich in Si, Al, Ca and Fe, which are elements eligible for brick production. Replacing clay soil by SSA can enhance brick properties, while reducing the primary raw material consumption for improving the sustainability of brick production. However, the P should be extracted before use in construction materials. This study investigates the potential for use of SSA, before and after P extraction, as a replacement of clay soil in unfired or fired bricks for a variety of soils.

10 different clay soils were used in the study, where 7 clay soils originated from brickworks that commercially produce fired bricks and 3 clay soils from excavation sites in Denmark. SSA from the Avedøre wastewater treatment plant in Copenhagen was used. For the investigations both raw and treated ash after an electrodialytic P extraction method were used.

The clay soil and SSA samples were characterised for chemical composition and mineralogy, and the clay soils additionally for clay content and Atterberg limits. Small brick discs (d=20 mm, h=3 mm) were made for all clay soils in their raw state (reference samples) and with 5 wt% replacement of the clay soil with the raw SSA or the treated SSA. The brick discs were produced at low forming pressure (3 MPa), to mimic the main forming method for regular-sized bricks at Danish brickworks. The brick discs were dried at 105 °C degrees before firing at 1050 °C (360 °C /h – 2 t hold at max. temperature). After production, the brick discs were tested for drying and firing shrinkage, density, porosity, and water absorption.

The characterisation of the clay soil samples showed differences in clay mineralogy and chemical composition. The Atterberg limits for all clay soils were within the recommended limits to produce either both unfired (adobe or compressed earth blocks) and fired bricks. The drying mass loss of the bricks increased when using SSA in the brick discs. This is because the SSA is more porous than the soil, and the mixes with SSA need more water added to be formable. On the other side, the drying shrinkage was not influenced negatively by the SSA, and for some clay soils, the drying shrinkage even decreased, which is

beneficial for unfired clay bricks. When firing the brick discs, the firing mass loss was correlated to the calcite content in the clay, and thereby replacing high carbonate content clay with SSA without calcite, reduced the firing mass loss. Similar results for the firing shrinkage, as for the drying shrinkage, the use of SSA resulted in the same or lower firing shrinkage. The results generally showed that the use of 5 % SSA in the brick disc samples did not significantly change the density, porosity or water absorption and that there was no significant difference between using the raw or P-extracted SSA, compared to the references. The main differences in brick properties between the different brick disc, were due to the different clay soil properties. Also, the bricks made from excavation soils showed similar brick properties to brickwork clay.

This preliminary study shows the potential for a variety of soil, both brickwork and excavation soils, and SSA after P extraction, in the production of both unfired and fired clay bricks.

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Siderite in cement mixes: impact on hydration and durability properties

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Keywords: iron carbonate, carbonation resistance

The possible incorporation of siderite (iron carbonate) into cementitious systems has been explored. Siderite is an important iron ore, found in many regions around the world, being Erzberg (in Austria) one of the largest deposits worldwide. Among the various applications of siderite, its potential use to partially replace cement in binders has been recently investigated, showing very promising results in terms of sustainability and durability enhancement. The mechanisms behind the effects caused by the presence of siderite in terms of hydration, strength development and resistance to aggressive substances, such as carbon dioxide and sulfate ions, are still not fully understood.

In our investigations, several aspects were addressed. In terms of hydration development, the presence of siderite in cementitious systems was observed to result in a retardation of the early hydration reactions and thus in a reduction of the early compressive strength of samples made with siderite-containing binders. This effect, related to the dissolution of siderite and the partial inhibition of the hydration reactions, can be controlled by the material fineness and thus the surface available for dissolution and interaction with the cementitious phases. On the other hand, the presence of siderite does not seem to impair the late strength of mortars/concretes. In terms of durability, mixes containing siderite showed better resistance against calcium leaching and sulfate attack, compared to mixes without siderite. Since lower leaching and sintering potential and also higher resistance to sulfate attack may be associated with lower portlandite contents, the resistance to carbonation needs to be assessed.

To test the behaviour of siderite-containing samples in terms of CO_2 exposure, mortar mixes were prepared with different binders consisting of CEM I 52.5R and 10 or 20% replacement of siderite, limestone, ankerite and quartz. Siderite and ankerite samples were obtained from the Erzberg mine in Eisenerz, Austria. Different fineness of the calcium and iron carbonates were tested. 4x4x16 cm prisms were cast and after 28 days of humid curing and 14 days of 57% RH and 20 °C storage, the mortar samples were placed in a carbonation chamber with 3% CO_2 concentration, 57% RH and 20 °C. The carbonation depth was tested after 0, 28, 70 and 90 days with a thymolphthalein indicator. In parallel, pastes samples prepared with the same binders and w/b ratio were exposed to the same conditions. At the testing times mentioned, hydration was stopped and X-ray diffraction (XRD) and Thermogravimetric (TGA) measurements were carried out.

The results obtained showed that, despite the low leaching and sintering potential (and high resistance to sulfate attack) of siderite-containing mixes, the resistance to carbonation was not considerably worse than that of mixes without siderite, containing quartz or limestone. According to the XRD results, lower portlandite contents were found in siderite-containing samples compared to those made with quartz and limestone, indicating either lower formation or consumption of portlandite. TGA data could not be directly used to quantify the portlandite content in the samples since siderite decomposition takes place at a similar temperature range as portlandite. A mass loss in that range could be attributed to both water from portlandite and/or CO_2 from siderite.

The unexpected good carbonation resistance of siderite-containing samples, similar to that of limestone and quartz-containing samples, despite the lower amounts of portlandite, seems to be related to the

formation of other phases, such as calcium carbonate and iron-containing hydrates, and the modification of the microstructure.

Siderite is a promising supplementary material that may be used to improve the properties of concrete and shotcrete and reduce their environmental footprint. To reach that goal, further studies are required to elucidate the mechanisms behind the behaviours observed in terms of hydration reactions and durability properties.

Silica-Supported Form-Stable Phase Change Materials for Enhancing Thermal Performance in Lime Mortars

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Keywords: lime mortars, Phase Change Materials (PCMs), form-stable, thermal performance, microstructure

1. Introduction

As concerns about sustainability and energy efficiency in the construction sector grow, lime-based mortars present a promising alternative due to their lower carbon footprint compared to conventional mineral binders. These mortars are not only environmentally friendly but also highly compatible with heritage conservation, making them ideal for the restoration of historical buildings. This study investigates the incorporation of form-stable phase change materials (PCMs), specifically silica-supported PCMs, into lime mortars to improve their thermal performance, enhancing both energy efficiency and thermal comfort.

PCMs absorb and release heat during phase transitions, reducing the need for active climate control systems and enhancing building thermal efficiency. The use of form-stable, silica-supported PCMs helps prevent material leakage during thermal cycling, ensuring greater long-term stability and reliability. This study focuses on the mechanical, thermal, and microstructural properties of lime-based mortars with silica-supported PCMs to assess their potential for improving energy efficiency and sustainability in construction applications.

2. Materials and methods

2.1 Materials

Air lime mortars were prepared using hydrated calcitic lime (CL 90-S) and fine calcitic sand (0–1 mm). The formulations included a superplasticizer (MasterCast GT 205), an adhesion enhancer (Casaplast KO09 S), and metakaolin (MK, Metaver) at 20% by weight of lime to improve mechanical performance. Silica-based form-stable PCMs (PCM5, melting point 5ºC; PCM25, melting point 25ºC) were added at 5%, 10%, and 20% by weight of lime (bwol). Two control mortars were prepared: CTRL-1, without PCM or MK, and CTRL-2, without PCM but with 20% bwol of MK for comparison (Table 1).

Table 1. Mortar formulations.

Mixture	MK (% bwol)	PCM5 (% bwol)	PCM25 (% bwol)
CTRL-1	0	0	0
CTRL-1	20	0	0
PCM5/0	0	10	0
PCM5/20	20	10	0
PCM25/0	0	0	10

PCM25/20	20	0	10

2.2 Mortar preparation

Fresh mortars were mixed by combining lime, sand, additives, metakaolin, and PCMs, with water fixed at 25 wt% to maintain uniformity. For testing, mortar disks (Ø = 55 mm, h = 20 mm) and cylindrical specimens (Ø = 30 mm, h = 40 mm) were prepared. Mortars were cured under controlled laboratory conditions (20°C ± 0.5°C, 60% ± 5% RH).

2.3 Characterization methods

The microstructure of the mortars was examined through Mercury Intrusion Porosimetry (MIP), conducted with a Micromeritics AutoPore IV 9500, to assess the porous structure and the impact of PCM incorporation.

Compressive strength was measured with a Frank/Controls 81565 press with a Proeti ETI 26.0052 device. Measurements were taken at 28, 91 and 182 curing days from three cylindrical specimens per condition.

Thermal conductivity (λ) was measured with a FOX50 Heat Flow Meter on specimens (Ø = 55 mm, thickness = 10 and 20 mm). Measurements at -5°C, 5°C, 15°C, 25°C, and 35°C captured λ in both PCM phases.

Differential Scanning Calorimetry (DSC) was used to assess the thermal behaviour of PCM-enhanced mortars, focusing on latent heat (ΔH_m, ΔH_c) and phase transition temperatures (T_m, T_c). Tests were conducted on a DSC25 over three heating-cooling cycles (-20°C to 50°C) at 5°C/min.

3. Results

The incorporation of PCM in lime-based mortars significantly affected their microstructure, as shown in Table 2. Although PCM addition increased the average pore diameter, open porosity remained relatively stable. Notably, PCM5 mixtures showed a moderate increase in pore diameter compared to the control, while PCM25 mixtures exhibited a more pronounced increase.

Table 2. MIP results at 91 curing days.

Mixture	Average pore diameter (μm)	Open porosity (%)
CTRL-1	0.3543	36.7
CTRL-2	0.3043	35.0
PCM5/0	0.3890	36.4
PCM5/20	0.3332	36.7
PCM25/0	0.6172	37.1
PCM25/20	0.4174	34.5

Although PCM incorporation increased pore size, the silica support reinforced the material, as indicated by the higher compressive strength in PCM-containing mixtures compared to PCM-free mortars, particularly at 91 and 182 days of curing (Figure 1a). This trend was evident for both the PCM5 and PCM25 formulations. Moreover, the addition of 20% MK further enhanced the strength, as seen when comparing CTRL-2 to CTRL-1, PCM5/20 to PCM5/0, and PCM25/20 to PCM25/0, likely due to the pozzolanic reaction.

Regarding thermal conductivity, Figure 1b shows the effect of PCM addition. A slight reduction in thermal conductivity was observed after incorporating both PCMs, suggesting that the heat flow towards and from the PCMs was still facilitated, allowing them to contribute effectively to thermal regulation.

As shown in Figure 1c, the DSC curves of PCM-containing mortars demonstrated their capacity to absorb and release heat through melting and crystallization phase transitions, confirming their potential to enhance thermal efficiency.

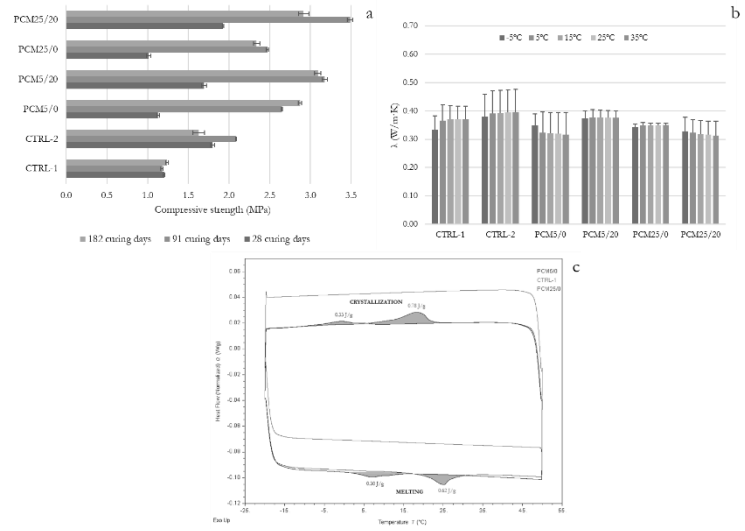

Figure 1. (a) Compressive strength values, (b) thermal conductivity measurements and (c) DSC curves of CTRL-1, PCM5/0 and PCM25/0 at 91 curing days.

4. Conclusions

The results demonstrate that silica-based form-stable PCMs are an effective strategy for enhancing the energy efficiency of lime mortars. The addition of these PCMs not only reinforces the sustainability of lime but also enhances its environmental benefits. This combination offers a promising solution for energy-efficient construction, while maintaining the compatibility of lime-based materials with heritage conservation applications.

Acknowledgments

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Study on Spurrite Formation Mechanisms under High-CO2 Concentration: Towards Implementation of Oxyfuel-Driven Cement Manufacturing

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The current industrial transformation requires innovative ideas to reduce the negative impact of traditional emission-intensive processes on the environment. The cement industry - accountable for around 8 % of global CO2 emissions - is facing the challenge of switching to green technologies to mitigate greenhouse gas emissions (GHG) in the manufacturing process. One of the most prominent solutions is carbon capturing, storage and/or utilization (CCU/S), to which Oxyfuel firing is regarded as one with the highest potential for cement manufacturing. In Oxyfuel systems, pure oxygen replaces conventional combustion air in the rotary kiln, thereby eliminating nitrogen from the flue gas and increasing CO2 concentrations to over 90 %. However, to operate under these conditions, the effects of the elevated CO2 partial pressure on clinkering reactions must be thoroughly examined, especially with respect to reactions in the pre-heater zone.

Evidence suggests that the high CO2 environment in the pre-heater can intensify build-up and cycle formation, which may significantly disrupt plant operation. Unlike in conventional cement plants, such build-ups cannot be easily removed without compromising system tightness. Current studies indicate that increased CO2 partial pressure shifts the chemical equilibrium toward the formation of spurrite [Ca5(SiO4)2CO3] a known build-up–forming phase that is highly dependent on CO2. Moreover, it is known that typical chloride impurities appear to catalyze spurrite formation, further enhancing the reaction based on chloride concentration.

A thermodynamic simulation was initially performed together with preliminary thermogravimetrical analysis (TGA) to understand spurrite formation under the given scenarios in industrial samples. From this, temperature ranges and reaction conditions for spurrite formation and decomposition were obtained, providing the starting point for the attempted experimental framework. Two scenarios were defined for this study. Synthetic raw meal and hot meal samples with different chlorine concentrations were prepared and heated up to 950 °C in a controlled CO2 atmosphere, following a specified heating program. During heating, *in-situ* X-ray diffraction (XRD) analysis was performed to monitor phase development. Subsequent Rietveld analysis was used to quantify the phases and to clarify the impact of the investigated parameters on both the emergence and suppression of spurrite.

Finally, correlations between the measured parameters were established, and the observed relationships were critically discussed providing first valuable approaches for future plant operation.

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Study on the effect of inorganic salt solution on the structure and properties of CO_2 mineralized cementitious materials

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Keywords:CO_2 mineralized cementitious materials, Ammonium salt, Microstructure enhancement, $CaCO_3$ crystal

Abstract

The effect of different inorganic salt solutions on the carbonation properties of CO_2 mineralized cementitious materials was investigated. Various analytical techniques were employed to characterize the hardening properties, product composition, microstructure and pore structure of the materials. The results show that the properties of carbonation-hardened materials depend on the degree of mineralization, the type of product formed, and the structure of calcium carbonate. The introduction of inorganic salt solutions changed the carbonation products and microstructure of the materials, reduced the Q4/Q3 content in silica gel, and stabilized the presence of spherulites, especially ammonium sulfate, diammonium hydrogen phosphate, and ammonium carbonate. These changes affected the pore structure. Among the different salts, the most significant improvement in the properties of the hardened materials was observed using 2 mol/L ammonium chloride solution. The compressive strength and carbonation increased by 42.04% and 7.33%, respectively, compared to the control. This improvement was mainly attributed to the increase in calcium carbonate content, which reduced the harmful pores and resulted in a more regular and stable structure of calcite particles. In this study, the key factors affecting the performance changes of CO_2 mineralized cementitious materials under different amounts of inorganic salt solutions were identified, which provides new possibilities for the development of high-performance CO_2 curing cementitious materials.

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Sustainable blended cement built on waste ashes and closed-loop principles

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Keywords: blended cement, incineration ashes, clinker replacement, sustainability, circular concepts.

The progressive reinforcement of environmental regulations within the European Union, alongside the ongoing phase-out of coal-fired power plants, is driving the transition toward a closed-loop economy. However, this shift presents significant challenges, particularly regarding the future availability of various supplementary cementitious materials (SCMs) such as coal fly ash (CFA), granulated blast furnace slag (S), etc. The economic feasibility of using these SCMs is increasingly limited by rising processing costs due to stricter environmental policies as well as regional production limitations, while the expansion of renewable energy sources is expected to further limit supply. In this context, the transition to low-carbon energy alternatives in Europe has led to a significant increase in the use of wood biomass as a low-emission energy source, generating wood biomass ash (WBA). Against this background, WBA, a by-product of wood combustion, is being investigated as a promising alternative with potential for integration into blended cements. Likewise, blended cements contribute to reducing the environmental impact of cement production by decreasing the amount of clinker required, which in turn lowers CO_2 emissions. Blended cements, which are often derived from industrial by-products, help address waste disposal challenges and promote the integration of closed-loop principles by minimizing waste. Therefore, blended cement concrete containing SCMs such as WBA offers a cost-effective solution to mitigate economic, environmental, and societal impacts, thereby supporting a more sustainable triple bottom line. This illustrates the necessity of engaging both the community and the traditionally conservative construction industry in these initiatives, as such involvement is fundamental to fostering the acceptance of alternative, locally available waste materials like WBA, and to advancing their incorporation into the development of next-generation blended cements.

This paper provides insights into the functional role of WBA as one of the main constituents in the formulation of a new blended cement, classified as CEM II/B Portland-composite cement, with an optimised proportion of WBA. Two innovative blends were formulated, incorporating clinker, gypsum, CFA, and either WBA1 or WBA3, alongside a selection of minor additional constituents. The WBAs were incorporated at 10% and 16% by weight, while the proportions of the other components were specified by the manufacturer and are considered proprietary. The research evaluated the viability of WBA in blended cement across three key phases: the binder phase, the mortar phase, and the concrete phase. This approach systematically examined the chemical composition, physical properties, and reactivity of various binder blends, providing a foundation for determining the optimal WBA proportion and refining the design of both mortars and, ultimately, concrete formulations.

Prior to concrete mixing, the blended pastes were assessed for water demand (standard consistency), setting time, and soundness. The influence of each blend on mortar performance was evaluated through an analysis of fresh-state properties, as well as compressive and flexural strength testing at 2, 7, and 28 days of humid

curing. Although the incorporation of WBA resulted in a reduction in setting time and an increase in water demand, the volume stability of the blends was not compromised. These findings suggest that the inclusion of WBA, at both proportions, can significantly enhance the mechanical properties of mortars, while also offering substantial potential for advancing sustainability and optimizing overall performance. Beyond the properties previously discussed, the compressive strength of concrete mixes after 28 days has been recognized as the initial parameter for assessing the performance of the new blended cements incorporating WBA. From the compressive strength values presented in Figure 1, it is evident that the incorporation of both WBA1 and WBA3 into the cementitious binder system improves the compressive strength of concrete across all blending ratios. Notably, concrete mixes prepared with blended cement with a higher proportion of WBA3 (16 wt.%) showed a 20% increase in compressive strength compared to the control mix made with control Portland-composite cement.

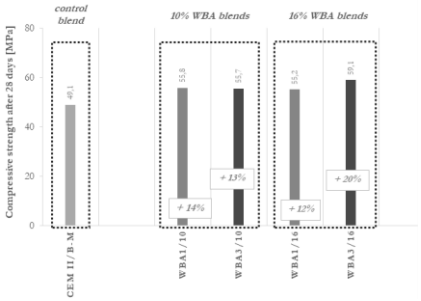

Figure 9. Compressive strength of concrete with varying WBA content (10&16%) and types, compared to the control blend

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Synthesis and hydration of Belite-Ye'elimite-Ferrite cements with different phase compositions and various sulfate sources

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Keywords: BYF, synthesis, belite, ye'elimite, ferrite

Introduction

Belite-ye'elimite-ferrite (BYF) cements are a more sustainable alternative to Portland cements, as the CO_2 emissions related to their manufacturing are considerably lower, partially due to a lower clinkering temperature (1250°C). Moreover, the presence of ye'elimite ($C_4A_3\bar{S}$[1]) allows to obtain cement composites with high early compressive strengths. However, the course of hydration depends on multiple factors, including the proportions of the main clinker phases and the presence of an additional sulfate ions source. Therefore, the goal of this study was to synthesize BYF clinkers characterized by different belite, ye'elimite and ferrite contents. Then, the hydration of these clinkers mixed with different amounts of anhydrite or gypsum was studied.

Methodology

Belite-ye'elimite-ferrite clinkers with target B/Y/F compositions of 50/30/20, 60/20/20 and 40/40/20 were obtained through solid state synthesis from analytical grade $CaCO_3$, Al_2O_3, Fe_2O_3, $CaSO_4 \cdot 2H_2O$ and SiO_2. The samples were sintered at 1300°C for 1.5 hours and ground in a laboratory ball mill to a Blaine's specific surface area of 5000 cm^2/g. Phase composition of the clinkers was determined using a PANalytical Empyrean X-ray diffractometer equipped with a Cu/Ni lamp operating at 35 kV/16 mA. Rietveld analysis was carried out using X'Pert Highscore Plus 5.1 software combined with ICSD database. The obtained clinkers were mixed with a sulfate source (gypsum or anhydrite) at two $CaSO_4/C_4A_3\bar{S}$ molar ratios (1.5 or 2.0) to form cements. The heat of hydration of these cements was measured at 25°C using a TAM Air isothermal microcalorimeter. Finally, the cements combined with gypsum at a $CaSO_4/C_4A_3\bar{S}$ molar ratio of 1.5 were used to obtain mortars by mixing them with a 0.125-2 mm fraction of standard EN 196-1 sand (cement-to-sand ratio of 1:3) and distilled water (water-to-cement ratio of 0.5). Cubic samples (dimensions of 20 x 20 x 20 mm) were molded and their early compressive strength (after 1, 2 and 7 days of curing) was determined using an Automax Controls 5 hydraulic press.

Results

The phase compositions of the obtained clinkers, calculated by Rietveld method, are presented in Figure 1. In all three cases, the content of brownmillerite was lower than the designed value, reaching approx. 15-17%. This result is most likely related to the fact that Fe^{3+} ions can enter the ye'elimite structure substituting aluminum and stabilizing the phase, thus lowering the amount of iron available for ferrite formation. Consequently, the ye'elimite content in all clinkers was slightly higher than the desired values. Moreover, in all samples, grossite (CA_2) was formed as an additional phase.

[1] In cement chemist notation: C – CaO, A – Al_2O_3, F – Fe_2O_3, S – SiO_2, $\bar{S}$ – SO_3.

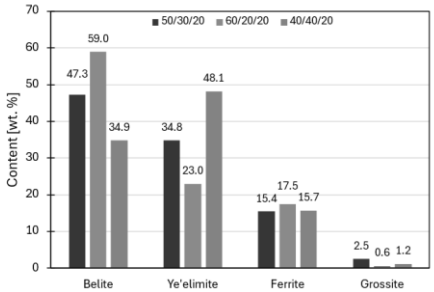

Figure 1. Phase composition of the obtained clinkers

The amount of added sulfates had the greatest impact on the heat release rate and cumulative heat evolved in the early stage of hydration (Figure 2). The heat evolution rate in the first 30 minutes of reaction increased with the $CaSO_4/C_4A_3\overline{S}$ molar ratio. Later on, the source of sulfate ions had more influence on the course of hydration and thus, the cumulative heat evolved after 41 hours (Figure 3). The full width at half maximum (FWHM) of the main exothermic effect is higher in the case of gypsum, while the use of anhydrite splits the effect into two distinct peaks with lower FWHMs. The cumulative heat of hydration increases with the amount of ye'elimite.

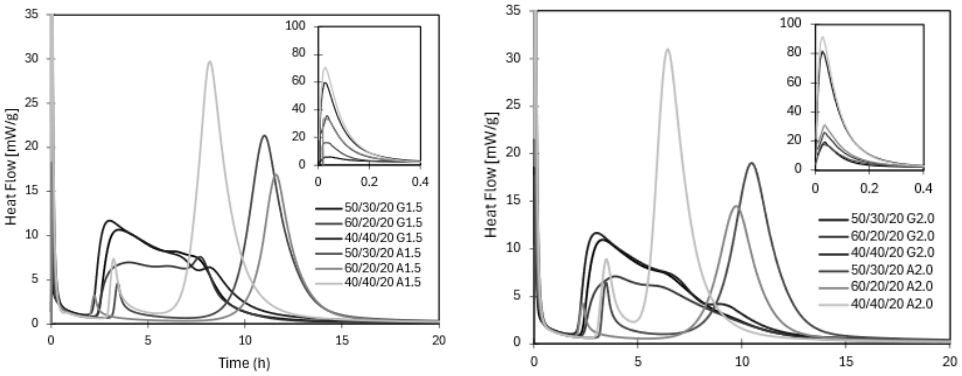

Figure 2. Heat evolution of clinkers hydrating in the presence of gypsum (G) and anhydrite (A)

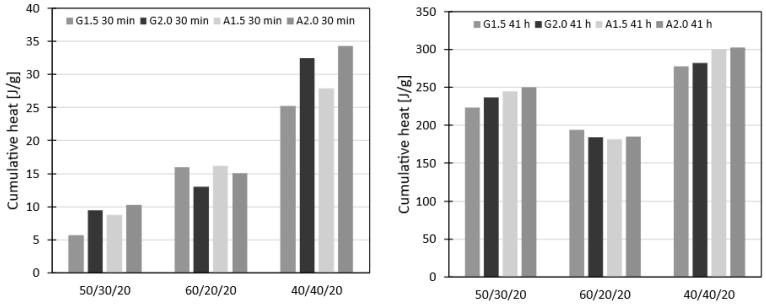

Figure 3. Cumulative heat of hydration

The compressive strength of the samples (Figure 4) depends on the hydration of the most reactive phase – ye'elimite. The strength gains observed between 1 and 7 days of curing were the lowest for the 60/20/20 mortar, containing the least ye'elimite. The compressive strength of the 40/40/20 sample showed an increasing trend. Meanwhile, the strength of the 50/30/20 mortar decreased from approx. 20 to 17 MPa between the first and second day of hydration. Afterwards, it increased back to approx. 20 MPa.

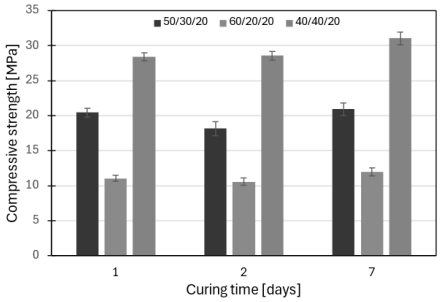

Figure 4. Compressive strength of mortars

Conclusions

During BYF clinker synthesis, the ye'elimite content in the final products tends to be lower than expected as the Fe^{3+} ions can build into the ye'elimite structure, stabilizing the phase. The heat evolution rate in the first 30 minutes of hydration increases with $CaSO_4/C_4A_3\overline{S}$ molar ratio of the clinkers. Afterwards, the sulfate ions source has more influence on the course of the reaction and the cumulative heat evolved after 41 hours, with a higher rate of heat evolution observed for anhydrite. Additionally, the amount of ye'elimite present in the system determines the early compressive strength of BYF cement mortars.

Acknowledgement

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Synthesis and Reactivity of Chlorellestadite: A Novel Binding Mineral Phase

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Keywords: Chlorellestadite; Mineral Synthesis; Carbonation curing; Carbonation reactivity; Thermodynamics calculations

Introduction

The cement industry faces mounting pressure to reduce its carbon footprint without compromising material performance. A promising approach involves utilizing alternative fuels and waste-derived raw materials to lower CO_2 emissions. This practice, however, leads to the formation of minor amount of water-insoluble chlorine-containing mineral phases, particularly chlorellestadite (CE), in kiln systems. Previous research has demonstrated that CE forms during the synthesis of C_2S-based eco-clinkers using municipal solid waste incineration byproducts, and preliminary findings suggest it possesses significant carbonation reactivity. To overcome current limitations in adopting alternative fuels and raw materials more extensively, this study focuses on synthesizing pure CE to systematically investigate its hydration and carbonation behavior. Meanwhile, the feasibility of using this novel mineral as stand-alone binder or SCM is validated.

Methodology

Synthesis and Characterization of CE:

CE was synthesized CE at 1100°C using stoichiometric mixtures of CaO, SiO_2, $CaSO_4$, and $CaCl_2$, guided by thermodynamic calculations. The synthesized CE was characterized using X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), and scanning electron microscopy (SEM). Carbonation reactivity was assessed by subjecting CE pastes to CO_2 curing (2 bars, 24 h), followed by mechanical and microstructural analyses.

Application as SCM:

A binary cement system with CE up to 40 wt% was prepared. Paste samples were compacted, carbonation-cured (2 bars, 24 h), and subsequently hydrated. Compressive strength, CO_2 uptake, mineralogy (QXRD, FTIR), pore structure (mercury intrusion porosimetry, MIP), and leaching behavior were evaluated.

Results and Discussion

Carbonation Reactivity of CE:

It was demonstrated that CE exhibits weak hydraulic properties, developing only 1.5 MPa after 1-day hydration but achieving 25.8 MPa under carbonation curing, with 4.8% CO_2 uptake. Carbonation products included vaterite, gypsum, calcium chloride, and silica gel, confirmed by XRD and NMR. SEM revealed rod-like CE crystals and fibrous C-S-H clusters. Leaching tests showed elevated chloride levels (480 ppm), suggesting CE is only suitable for non-reinforced applications.

Performance as SCM:

CE substitution reduced early strength due to dilution but enhanced 28-day strength by 21.1% (93.4 MPa for 20% CE). Carbonation-generated secondary gypsum promoted ettringite formation during hydration, refining pore structure (reduced capillary pores). Thermodynamic modeling and pH measurements

confirmed that higher gypsum content and lower alkalinity favored larger ettringite crystals, improving microstructure.

Conclusion

These studies underscore CE's potential as a binding mineral. Its carbonation reactivity enables CO_2 sequestration and strength development, while its use as an SCM reduces cement demand and enhances late-age performance. Key takeaways include:

- CE synthesis at 1100°C is optimal, with carbonation curing yielding 25.8 MPa strength.
- As an SCM, CE refines pore structure via secondary gypsum and ettringite, boosting 28-day strength by 21%.
- Leaching risks limit CE to non-reinforced applications, such as dry-cast products.

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Synthesis, structure and hydration study of pure Belite, Ye'elimite, and Ferrite BYF cement phases

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Keywords: BYF cements, synthesis, ye'elimite, mayenite, hydration.

Introduction

Belite-ye'elimite-ferrite (BYF) cements are a potential more eco-friendly alternative to Portland cement. Their production is carried out at lower temperatures of 1250-1350°C and the clinker is easier to grind, resulting in a reduction in milling process costs and they have about 30% less carbon footprint. BYF cements consist of three main phases, belite (C_2S), ye'elimite ($C_4A_3\bar{S}$), and ferrite (C_4AF), the proportion of which significantly affects the hydration process, formed products, microstructure, and performance, especially setting time, heat release and compressive strength development. Furthermore, latest research showed a significant influence of the content of mayenite ($C_{12}A_7$), whose presence in the system results from the decomposition of ye'elimite with a high content of iron ions. Fe^{3+} ions are added to stabilise the cubic form of ye'elimite. Despite the low content of $C_{12}A_7$ (less than 5%), its rapid dissolution accelerates the formation of ettringite, shortens the setting time and significantly modifies the hydration process of $C_4A_3\bar{S}$. Understanding the conditions of formation of these phases and their influence on the properties of BYF cement systems enables the proper selection of the composition of the raw material and calcination conditions. This work describes the entire methodology for the high temperature synthesis of pure phases (C_2S, $C_4A_3\bar{S}$, C_4AF, $C_{12}A_7$) in contrast to those previously reported in the literature. The aim of this research is to develop a simple synthesis method without the need to compact samples under pressure before calcination. In this study, the structural characterisation of the pure phases and a comparison of their hydration processes was carried out.

Methodology

Pure reagent $CaCO_3$, α-Al_2O_3, amorphous SiO_2, Fe_2O_3, and $CaSO_4 \cdot 2H_2O$ were used to phase synthesis. Belite was synthesised with a 5% addition of B_2O_3 used as a stabiliser for high-temperature β polymorph. All sinterings was carried out in two stages. First, the samples were heated at 5°C/min to 900°C and held at that temperature for 30 minutes to decompose the calcium carbonate. Then, they were heated at 10°C/min to target synthesis temperature. A general scheme of the pure phase synthesis procedure is shown in Figure 1. Table 1 shows the preparation and calcination parameters for each of the synthesised phases. Obtained phases were studied by X-ray Diffraction combined with Rietveld analysis using a PANalytical, Empyrean diffractometer CuKa1 (1,54178 Å, range 5-90° 2θ, step 0,008° 2θ). Fourier Transform Infrared (FT-IR) measurements were performed in the middle infrared range (MIR) with a Bruker Vertex 70v vacuum spectrometer using the standard KBr pellet method. Data were post-processed in Bruker OPUS 7.2 software.

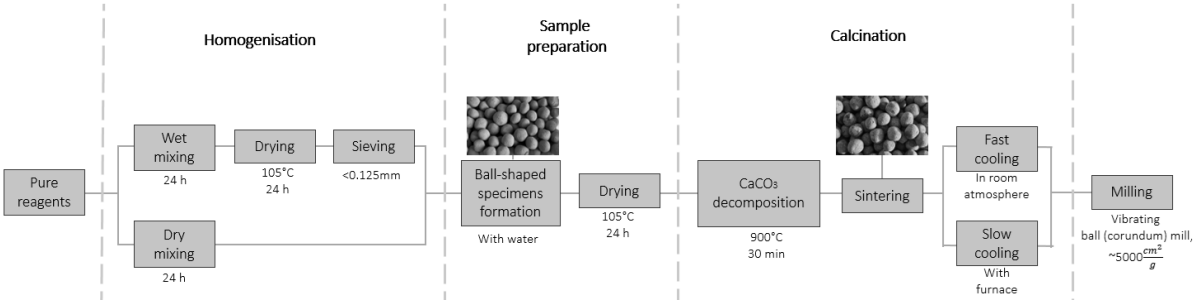

Figure 1. Synthesis procedure.

Table 1. Phase synthesis parameters.

Conditions	Belite	Ye'elimite	Brwnmillerite	Mayenite
Raw material assumptions	Stechiometric CaO/SiO_2 ratio and 5% B_2O_3	Stechiometric CaO/Al_2O_3 ratio and 5% excess of $Ca_2SO_4 \cdot 2H_2O$	Stechiometric $CaO/ Al_2O_3 / Fe_2O_3$ ratio	1.47% excess of CaO
Homogenisation	Dry	Wet	Dry	Wet
Temperature [°C]	1250	1300	1320	1430
Time [h]	3.0	4.0	3.5	1.0
Sintering	Solid-state	Solid-state	Solid-state	Liquid
Cooling	Fast (quenching)	Fast (quenching)	Slow	Fast (quenching)
Purity [%]	100	89,1	100	100

Results

The composition and purity of the synthesised phases were verified by X-Ray diffractometry XRD with Rietveld analysis. Figure 2 shows a diffractogram of the synthesised belite (ref. code 96-901-2793) (Table 2) with characteristic reflections present at 19.122, 31.078, 32.041, 32.599, 41.127 [°2θ]. For ye'elimite (ref. code 96-400-1773) (Figure 3, Table 3) characteristics peaks were observed at 18.017, 23.646, 33.719, 41.546, 56.591 [°2θ]. Brownillerite (ref. code 96-900-3349) (Figure 4, Table 4) reflections occurred at 12.176, 32.119, 33.466, 33.870, 44.125, 47.066 and 50.204 [°2θ]. Mayenite (ref. code 96-430-8077) (Figure 5, Table 5) characteristic peaks were present at 18.110, 27.821, 33.397, 36.693, 46.665, 55.203, 57.476 [°2θ].

Table 2. Crystallographic parameters of the obtained belite.

Crystal System	Monoclinic
Space Group	P121/c1
Cell parameters	
a	5.5070
b	6.7510
c	10.4260
Unit cell volume [10^6 pm^3]	344.83
Density [g/cm^3]	3.32

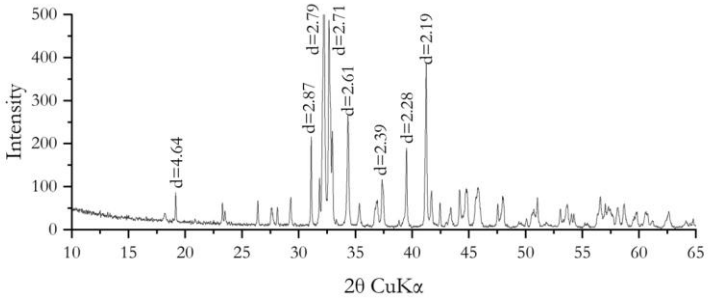

Figure 2. X-ray pattern of belite.

Table 3. Crystallographic parameters of the obtained ye'elimite.

Crystal System	Orthorhombic
Space Group	Pcc2
Cell parameters	
a	13.0360
b	13.0350
c	9.1680
Unit cell volume [10^6 pm^3]	1557.87
Density [g/cm^3]	2.60

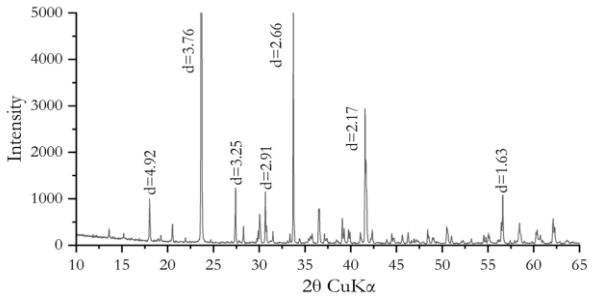

Figure 3. X-ray pattern of ye'elimite.

Table 4. Crystallographic parameters of the obtained brownmillerite.

Crystal System	Orthorhombic
Space Group	Ima2
Cell parameters	
a	14.5260
b	5.5690
c	5.3510
Unit cell volume [10^6 pm^3]	432.87
Density [g/cm^3]	3.79

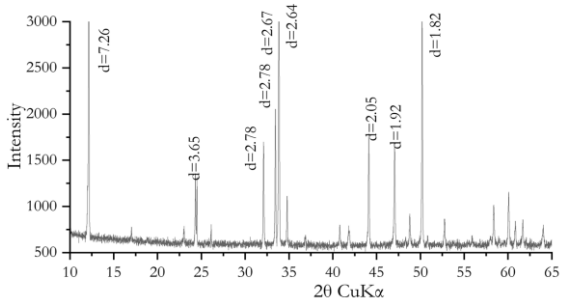

Figure 4. X-ray pattern of brownmillerite.

Table 5. Crystallographic parameters of the obtained mayenite.

Crystal System	Cubic
Space Group	I-43d
Cell parameters	
a	11.9920
b	11.9920
c	11.9920
Unit cell volume [10^6 pm^3]	1724.55
Density [g/cm^3]	2.66

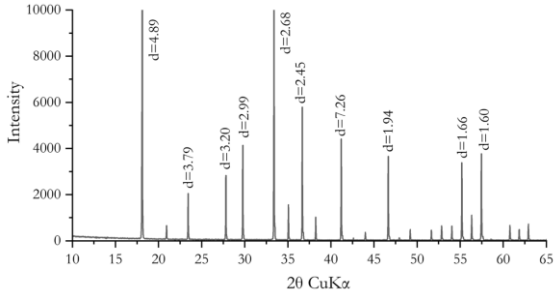

Figure 5. X-ray pattern of mayenite.

Conclusions

The research presents a complete and simplified synthesis methodology of pure BYF cements phases. Moreover, it compares their hydration, which has not been described in the literature. The described synthesis procedure allowed to obtain 100% pure belite, brownmillerite and mayenite phases as shown by Rietveld's analysis. The only phase obtained with a lower purity was ye'elimite (89.1%), the synthesis of which will be repeated with an $Ca_2SO_4 \cdot 2H_2O$ excess increeased to 9%. The comparison of the released hydration heat allows to determine the influence of the individual phases on the hydration of multiphase systems.

Acknowledgement

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The effect of the Na2O to SO3 molar ratio on the performance of Portland cement clinker in the presence of MgO

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Keywords: cement clinker, hydration, SO_3/Na_2O ratio, MgO

With the decreasing availability of high-purity raw materials, the use of alternative raw materials (e.g. low-purity natural raw materials, industrial by-products, etc.) has become inevitable in Portland cement clinker production. This introduces some minor elements into the system, which can affect the properties of cement clinker products and therefore the final cement binders. Notably, magnesium (Mg) is the most common minor element in the alternative raw meals for clinker production.

Therefore, to assess the impact of the significant presence of Mg, this project investigates the effect of the Na_2O/SO_3 molar ratio (N/S) on cement clinker properties in the presence of MgO. Small amounts of sodium (Na) and sulphur (S) are usually present in cement clinker, and the Na_2O/SO_3 ratio can significantly affect its mineralogical composition, leading to a change in cement hydration behaviour. To achieve the goal, clinkers have been prepared at different compositions. The Na_2O content is fixed at 1 wt.%, and the SO_3 content is adjusted to change the N/S ratio (N/S= 0.5, 1 and 1.5). The clinker characterization, such as the clinker phase assembly, the dissolution of minor elements in each clinker phase and the microstructure of clinker grains, has been conducted using X-ray diffraction (XRD), scanning electronic microscopy (SEM). The hydration properties of the resulting clinker have also been investigated using isothermal calorimetry, XRD, SEM and thermogravimetry (TG).

From the mineralogical composition of the clinker, as shown in Table 3, it can be concluded that in the absence of MgO, the incorporation of Na and S reduces the alite formation while promoting the belite formation, because SO_3 can stabilize belite. The alite content decreases with decreasing N/S ratio, however, when MgO is present, the co-incorporation of MgO can stabilize alite. As displayed in Table 4, the MgO content dissolved in alite and belite increases with the increase of MgO content in the raw meals up to a maximum of ~1.5 wt.% and ~0.5 wt.% respectively, and the incorporation of Na_2O and SO_3 did not exhibit a significant influence on the MgO dissolution behaviour. For the dissolution of Na and S ions, they appear to dissolve more in belite than in alite. Additionally, as the N/S ratio decreases, Na content in silicates decreases, while S content increases. These results indicate that the dissolution of Mg and the dissolution of Na and S ions in silicates do not influence each other, but the dissolution of Na and S can affect each other, due to the formation of thenardite (Na_2SO_4) identified in the XRD data.

Table 3. Phase content of clinkers obtained via XRD.

Clinkers	N/S	Clinker phase (wt.%)							
		Alite	β-C_2S	α'-C_2S	Aluminate	Ferrite	Thenardite	Periclase	Lime
0M	-	60.5	21.9	-	6.1	10.5		-	0.9
0M1N0.67S	1.5	34.2	13.4	29.4	10	7.4	0.7	-	5
0M1N1S	1	7.7	34.4	33	6.7	9.4	0.7		8.1
0M1N2S	0.5	-	55.8	18.9	3.1	11.9	0.7	-	9.8
1.5M	-	64.3	17.9	-	0.8	16		-	
1.5M1N0.67S	1.5	62.7	13.1		12.1	11.1	0.9		
1.5M1N1S	1	60.5	17.8		8.6	12	0.9		
1.5M1N2S	0.5	44.4	29.6		8.3	14.9	0.9		1.9
3M	-	64.3	16.9	-	2.9	12.9		2.3	
3M1N0.67S	1.5	59.7	14.4	-	11.6	11.5	0.5	2.4	
3M1N1S	1	59	18.5		7.5	11.6	0.7	2.3	
3M1N2S	0.5	44.8	31		7.1	11.7	1.3	2.4	1.7

Note: naming rules: 0M1N2S means the MgO weight content is 0%, the Na_2O content is 1%, and SO_3 content is 2%.

Table 4. Oxide composition of each phase obtained via EDX (wt.%).

Clinker	N/S	**Alite**			**Belite**		
		MgO	Na_2O	SO_3	MgO	Na_2O	SO_3
0M	-	0.15	-	-	0.07	-	-
0M1N1S	1	0.16	0.16	0.29	0.10	1.01	1.76
0M1N2S	0.5	-	-	-	0.11	0.86	2.83
1.5M	-	1.12	-	-	0.49	-	-
1.5M1N0.67S	1.5	1.09	0.19	0.26	0.47	1.22	1.75
1.5M1N1S	1	1.07	0.17	0.33	0.50	1.04	2.10
1.5M1N2S	0.5	1.19	0.13	0.52	0.54	0.86	2.98
3M	-	1.60	-	-	0.64	-	-
3M1N0.67S	1.5	1.46	0.19	0.24	0.47	1.21	1.74
3M1N1S	1	1.48	0.17	0.34	0.48	1.13	2.10
3M1N2S	0.5	1.43	0.13	0.52	0.51	0.77	2.76

The incorporation of MgO can delay the hydration of clinkers, as indicated by the heat flow of hydration (the black curves in Figure 1), but the co-incorporation of Na and S can retrain the retardation effect caused by MgO. The hydration can be accelerated with a low N/S ratio (blue curves), but in the clinker systems with Na_2O and SO_3, the generated Na_2SO_4 would affect the hydration. Therefore, more work will be needed to consider the effect of Na_2SO_4 on the hydration rates.

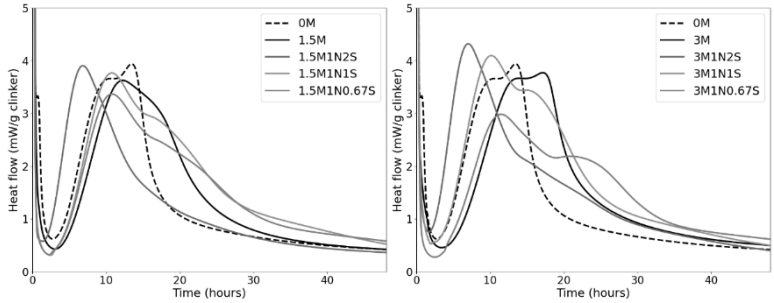

Figure 10. The heat flow of hydration for clinker with MgO at various S/N molar ratios (6 wt.% of gypsum was mixed into the clinker).

In conclusion, the dissolution of MgO and Na_2O/SO_3 in alite and belite is independent of each other. The incorporation of Na and S ions can promote belite formation and reduce alite formation, but the co-addition of MgO can re-stabilize alite. Therefore, in the raw meals with Na_2O and SO_3, the addition of MgO is advantageous and the N/S ratio should be higher than 1 to maintain the sufficient formation of

alite. The single incorporation of MgO can retard the hydration, and the co-incorporation of Na and S mitigate the retardation caused by MgO.

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The influence of biochar on mechanical strength and CO_2 mass gain in γ-C_2S carbonated compacts

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Keywords: biochar, γ-C_2S, CO_2, carbonated, sequestration

The construction sector has grown significantly in recent years due to increasing demand for ecologically friendly an d efficient building techniques. Among advancements, gamma-dicalcium silicate (γ-C_2S) concrete printing is a promising process that has the potential to transform the construction industry. γ-C_2S has high potential for applications as a construction material due to its high carbonation reactivity and the additional advantage of CO_2 absorption capacity. γ-C_2S is commonly used as a carbonate binder due to its rapid and spontaneous reaction with CO_2 in the presence of moisture, resulting in a material with exceptional compressive strength. Accelerated carbonation improves the early-age strength of cement-based materials and promotes the sequestration of CO_2. Gamma dicalcium silicate (γ-C_2S) is recognized for its slow hydration and reactivity; it reacts with CO_2 to undergo carbonation. This process produces calcium carbonate ($CaCO_3$) and calcium silicate hydrate (C-S-H), both of which contribute to the development of strength in the material. Rice husk biochar was used in this investigation to incorporate into γ-C_2S carbonated compacts, which were produced at 500°C for 2 hours. The production of biochar from agricultural waste serves multiple purposes, economically substituting for a portion of γ-C_2S while also aiding in CO_2 sequestration and protecting the environment from the release of methane, CO_2, and N_2O, which are generated during the decomposition of agricultural waste. The study investigated the carbonation of biochar-enhanced γ-C_2S compacts to determine the optimal amount of biochar to incorporate into γ-C_2S and the impact of varying biochar percentages on the strength development and CO_2 mass gain of biochar-enhanced γ-C_2S carbonated compacts. The influence of biochar on the CO_2 mass gain of biochar-enhanced γ-C_2S in carbonated compacts, as well as the mechanical strength and carbonation behavior of γ-C_2S compacts, was investigated. Biochar was introduced as an additive material to γ-C_2S to evaluate its impact on the mechanical strength and CO_2 mass gain of γ-C_2S carbonated compacts. Experimental results indicate that the incorporation of biochar into calcium silicate-based materials has garnered attention for its potential to mitigate CO_2 emissions and enhance sustainability. The powders of γ-C_2S and biochar were physically mixed first, then blended with water at a water-to-solid (w/s) ratio of 0.15. The mixture was compressed into columnar samples (20 mm diameter × 20 mm height) under a pressure of 1.88 MPa for 3 minutes, followed by carbonation for 24 hours. The impact of biochar on γ-C_2S carbonated compacts: the experiment was conducted with the water-to-solid ratio of 0.15 and the carbonated compacted samples mixed as fellows: prepared percentages of γ-C_2S and biochar respectively: 94.74% & 5.26%, 97.3% & 2.7%, 97.8% & 2.2%, 98.36% & 1.64%,

98.9% & 1.1%, and some samples with 100% γ-C_2S. The carbonated, compacted samples' compressive strengths were determined to be 57.8 MPa, 128 MPa, 113.0 MPa, 74.0 MPa, 86.1 MPa, and 132.8 MPa, respectively. Additionally, the CO_2 mass gain of biochar-enhanced γ-C_2S carbonated compacts was found to be as follows: 15.56%, 16.88%, 16.16%, 15.62%, 15.37%, and 15.2%, or 155.56 (g/kg), 168.84 (g/kg), 161.60 (g/kg), 156.20 (g/kg), 153.70 (g/kg), and 152.0 (g/kg) respectively. Compressive strength measurements show that biochar-enhanced γ-C_2S compacts have worse mechanical characteristics than pure γ-C_2S samples. Adding biochar to γ-C_2S carbonated compacts can increase their CO_2 mass gain due to improved CO_2 uptake. The experimental results confirm the development of stable carbonation products, which reinforce the tight matrix. These findings show that biochar can serve as a sustainable ingredient to optimize γ-C_2S carbonation compacts for eco-friendly construction applications. This study investigated biochar-enhanced γ-C_2S carbonated compacts to determine the optimal amount of biochar to incorporate into γ-C_2S and the impact of varying biochar percentages on the development of strength and the CO_2 mass gain of biochar-enhanced γ-C_2S carbonated compacts. These findings help optimize the design and implementation of biochar-enhanced γ-C_2S-based materials for sustainable construction. The experimental results demonstrate that biochar-enhanced γ-C_2S can enhance the CO_2 mass gain of biochar-enhanced γ-C_2S carbonated compacts, providing an important guideline for future agricultural resource utilization of waste and industrialized production in the green construction industry.

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The Influence of Metakaolin to Vaterite Ratio on the Properties of Vaterite Calcined Clay Cement: Microstructure, and Mechanical Performance

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Keywords: Calcined Clay Cements, Vaterite, Metakaolin, Compressive Strength, Microstructure

Introduction

Cement production is responsible for approximately 8% of global CO_2 emissions, necessitating the development of sustainable alternatives. One widely studied approach involves the use of supplementary cementitious materials (SCMs), such as limestone and calcined clays, to partially replace ordinary Portland cement (OPC). Among these, Limestone Calcined Clay Cement (LC3) has demonstrated potential in reducing carbon footprints while maintaining mechanical performance.

Despite the extensive study of LC3 binding systems, recent advancements in carbon reduction and utilization technologies have enabled the scalable production of vaterite, a metastable and more reactive polymorph of calcium carbonate. This development presents a promising but underexplored opportunity for sustainable binder production.

This study examines Vaterite Calcined Clay Cement (VC3) as a sustainable binder, focusing on how the metakaolin-to-vaterite (MK/V) ratio influences workability, microstructure, and mechanical properties. By addressing this gap, this research contributes to optimizing VC3 formulations and advancing low-carbon cement technology.

Methodology

Nine mortar compositions were investigated: seven VC3 mixtures, one LC3 mortar, and one OPC mortar serving as control. In all VC3 mixes, OPC and gypsum were fixed at 50% and 5% of the total binder weight, respectively. The MK/V ratio in the VC3 series ranged from 1 to 3 in seven increments. The LC3 mortar contained 50% OPC, 30% metakaolin, 15% limestone, and 5% gypsum.

All mixtures, including the OPC and LC3 controls, were prepared with a water-to-binder (w/b) ratio of 0.5 and a sand-to-binder ratio of 3:1 by weight. The study examined the influence of the MK/V ratio on compressive strength, workability, and microstructure. Compressive strength was measured at 3, 7, 28, and 91 days, while workability was assessed using the flow-table test. Microstructure was analyzed via Scanning Electron Microscopy (SEM). The mix design is shown in Table 1.

Table 1. Mix design of laboratory composites

	Cement (%)	MK (%)	Gypsum (%)	Vaterite (%)	Calcite (%)	MK/V
OPC	100	0	0	0	0	0
LC3	50	30	5	0	15	0
VC3-1	50	22.5	5	22.5	0	1.00
VC3-1.5	50	27	5	18	0	1.50
VC3-1.75	50	28.64	5	16.36	0	1.75
VC3-2	50	30	5	15	0	2
VC3-2.25	50	31.16	5	13.84	0	2.25
VC3-2.5	50	32.15	5	12.85	0	2.50
VC3-3	50	33.75	5	11.25	0	3.00

Results and Discussion

The compressive strength (CS) development of the VC3 mortars exhibited a nonlinear relationship with the MK/V ratio, similar to trends observed in LC3 systems. As the MK/V ratio increased from 1 to 3, CS initially improved for samples at 91 days of curing, reaching an optimal range of MK/V ratio between 2 to 2.5, before declining. This pattern indicates a delicate balance between the reactive components in the system. Mortars within this range achieved 99%–106% of the compressive strength of OPC at 91 days, surpassing the performance of LC3, which typically exhibits lower long-term strength than OPC.

The CS evolution varied significantly depending on the MK/V ratio and curing age. Mixtures with lower MK/V ratios exhibited rapid CS gains between 7 and 28 days, likely due to the early formation of hemi- and mono-carboaluminate (Hc and Mc) phases, which contribute to the initial strength development. These phases typically are observed along with a decrease in portlandite (CH) content. In contrast, MK/V ratios above 2 exhibited delayed but sustained strength gains, with a more pronounced increase between 28 and 91 days. This late-stage strength development is attributed to the formation of strätlingite, facilitated by the increased availability of aluminum from metakaolin reacting with portlandite. The reaction kinetics suggest that the balance of carbonate phases, MK, and calcium hydroxide reached a local equilibrium before 28 days, enabling later-stage strength improvements due to continued strätlingite precipitation. Additionally, the formation of strätlingite depends on Al_2O_3 present in the mix and the uptake of Al in C–S–H phases. These findings indicate that the MK/V ratio plays a crucial role in determining both early and late-stage strength evolution, impacting the overall performance of VC3 mortars.

Regarding workability, both VC3 and LC3 mortars showed reduced workability compared to OPC, likely due to lower cement content. However, VC3 mortars exhibited better workability than LC3 due to the spherical shape and wider particle size distribution of vaterite, which contrasts with the finer, more irregular morphology of metakaolin and limestone.

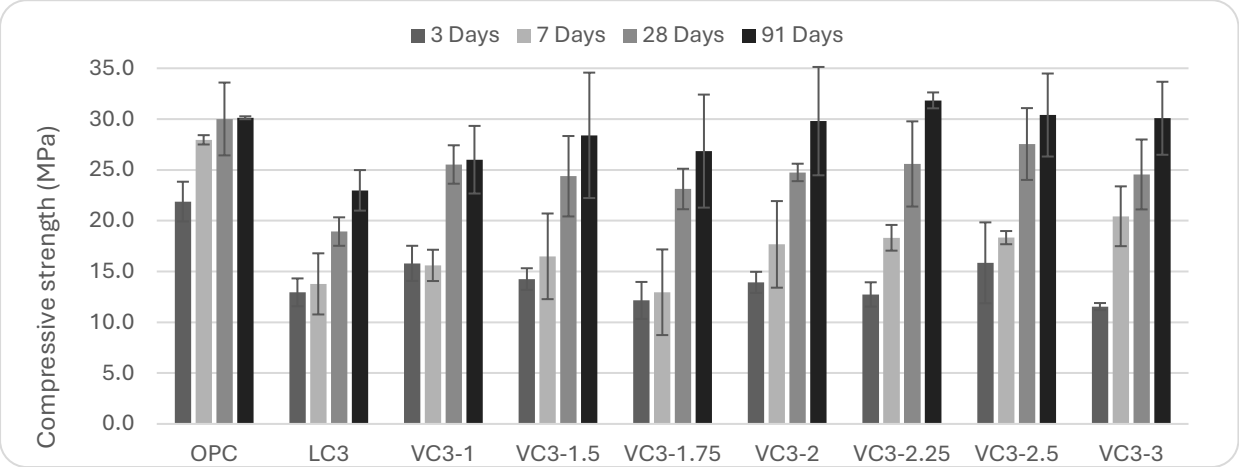

Figure 1. Compressive strength of laboratory composites

Conclusions

This study highlights VC3 as a promising low-carbon cement alternative. Optimizing the MK/V ratio enhanced compressive strength, surpassing both OPC and LC3 at later curing age. Strength development was linked to hydration phase evolution, confirmed by SEM analysis, showing reduced portlandite at later ages. Additionally, VC3 demonstrated superior workability compared to LC3, although workability declined at higher MK/V ratios. Given its potential for CO_2 reduction, further research should explore long-term durability, alternative hydration phase interactions, and fresh-state properties.

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The microstructure charateristics of cementitious material containing carboxylic acid ammonium

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Key words: Hydrophobicity;Permeability; Pore structure; Hydrodynamic effects.

Abstract

One of the most effective methods to improve durability of cementious materials is to resist the intrusion of water with aggressive ions by mixing with hydrophobic agent. In this study, the mechanism of carboxylic acid ammonium salt hydrophobic agent addition on hydrophobicityof cementitious materials is analyzed. Theimpact of hydrophobic agent on water adsorption, moisture diffusion and hydration products is investigated by experimental method. It is shown that carboxylic acid ammonium salthydrophobic agent performs the excellent water repellence. The results of water vapor sorption isotherm show that the addition of carboxylic acid ammonium salt increases the pore volume. The simplified analytical hydrodynamic model of cone type pore and Young's relationship is proposed to analyze the relation between characteristic parameters of pore and the permeability of cementitious materials. It can be concluded that the hydrophobicity results from the change of pore structure and the hydrophobic surface of cone region. These results provide the guidance to design the durability and develop the new hydrophobic agent used in cementitious material.

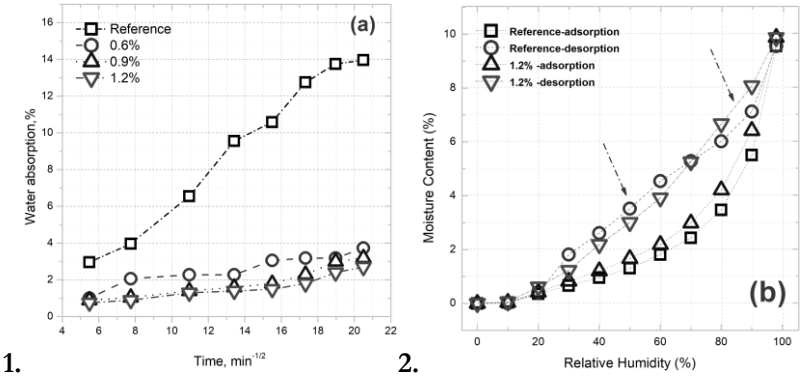

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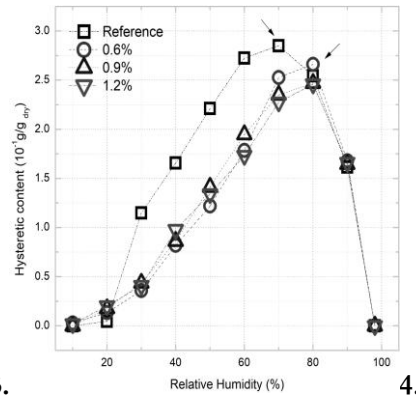
Fig.1 Water adsorption properties of mortars containing various amounts of hydrophobic agents.



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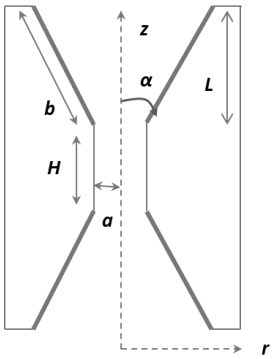

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Fig.2.Moisture sorption isotherms for cement pastes containing different amount of hydrophobic agent acquired across a range of relative humidity. Fig.3. The hysteretic curve with respect to pastes mass acquired across moisture sorption isotherms for cement pastes containing different amount of hydrophobic agent. Fig.4 An illustration of pore structure of cement paste in presence and in absence of hydrophobic agent including cylinder type pore and cone type pore, the thick solid line represents the hydrophobic surface.

Acknowledgment

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The shrinkage behaviour of in-situ polymerization modified cement paste

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Keywords: Cement paste, in-situ polymerization, auto-shrinkage, drying shrinkage

Cement-based materials, as quasi-brittle substances, exhibit a propensity for cracking and brittle fracture under practical service conditions, significantly undermining structural integrity and safety. In recent years, in-situ polymerization has emerged as a promising technique for enhancing the toughness of cementitious composites. Beyond its mechanical reinforcement capabilities, this method also facilitates rapid alterations in the rheological state of cement paste, enabling innovative applications such as improving the printability of 3D-printed concrete and the processing of woven cementitious textiles. However, the hydrogel formed through monomer polymerization exhibits pronounced hydrophilicity, rendering it susceptible to volumetric instability—undergoing dehydration-induced shrinkage upon water loss or expansion upon water absorption. Consequently, cement-based materials modified via in-situ polymerization face risks of volume instability. Despite this critical issue, systematic investigations into the shrinkage behaviour of such composites remain absent from the literature. Therefore, elucidating the shrinkage characteristics of these materials is imperative to provide theoretical guidance and practical solutions for their broader application.

This study comprehensively evaluates both early-age autogenous shrinkage and long-term drying shrinkage using corrugated tube tests and dial gauge measurements. Concurrently, hydration kinetics were monitored through isothermal calorimetry, while internal temperature evolution was tracked using embedded sensors. The Elasticity Modulus Measurement through Ambient Response Method (EMM-ARM) was employed for continuous assessment of stiffness development. Additionally, internal humidity fluctuations and water state transitions were quantified via humidity sensors and low-field proton nuclear magnetic resonance (1H-NMR) spectroscopy at varying curing ages. Mechanical performance was systematically examined across different monomer incorporation ratios.

The results demonstrate that in-situ polymerization significantly increases the deformation of cement pastes. Initially, during the first few hours of cement's contact with water, the polymerization shrinkage exacerbates the plastic shrinkage of the cement paste. The shrinkage reaches up to $15{,}000 \times 10^{-6}$ when the monomer content is increased to 10% of the cement paste. As monomers polymerize to form a cross-linked network, the distance between molecules decreases, leading to an overall reduction in volume. This substantial shrinkage causes surface delamination and cracking. Subsequently, the cement paste expands due to thermal dilation resulting from cement hydration, reabsorption of bleeding water, and the generation of hydration products. In-situ polymerization amplifies this expansion process. This occurs because the heat released during polymerization raises the temperature of the cement paste, while the polymers tend to expand with water absorption. Afterwards, the cement paste enters the autogenous shrinkage stage. When the monomer content is below 3%, autogenous shrinkage decreases compared to the control group, but increases when the monomer content exceeds 5%. Low monomer contents tend to form individual gel particles that fill the pores of the cement paste, reducing autogenous shrinkage, similar to the effect of superabsorbent resins. However, higher monomer contents form continuous polymer networks, which increase both the toughness and shrinkage of the cement paste due to higher water consumption. Furthermore, drying shrinkage increases with the incorporation of in-situ polymerization, and this shrinkage further intensifies as the dosage increases. The results of mass loss and internal humidity changes indicate that in-situ polymerization delays cement hydration, causing more water to be released into the air if the cement paste is unsealed. The polymer tends to shrink with water loss due to surface evaporation and ongoing cement hydration, leading to significant shrinkage of the cement paste overall. Additionally, the results for elastic modulus show that the rigidity of cement pastes significantly decreases with in-situ polymerization modification, causing more pronounced deformation.

While in-situ polymerization effectively enhances toughness, it simultaneously intensifies shrinkage at both early and late ages through three primary mechanisms: polymerization-induced contraction, hydrogel dehydration shrinkage, and matrix stiffness reduction. These findings underscore the necessity for controlled early-age curing conditions and the development of shrinkage-mitigation strategies to enable practical implementation of this modification technique. Future research should focus on polymer network optimization and internal curing agents to balance mechanical enhancement with dimensional stability.

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Thermal activation of magnesium oxychloride cement (MOC) based on half-calcined dolomite: Influence on (transient) mineral phase composition

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Keywords: Magnesium oxychloride cement (MOC), half-calcined dolomite, kinetic mineral phase development, thermal treatment, mineral binder

Introduction

Magnesium oxychloride cements (MOCs), also known as Sorel cements, were discovered in 1867 and are gaining renewed attention. They are especially interesting for the building industry, because of their environmental benefits, like their lower CO_2 footprint compared to Portland cement. Traditionally, calcined magnesite is used as magnesium oxide source for these cements. However, the availability of high-quality magnesite is limited to a few specific locations and as such depending on export restrictions and long distance imports. Using half-calcined dolomite as raw material could mitigate these drawbacks because of its abundant availability.

While it was already proven, that half-calcined dolomite can be used for MOCs, the influence of stoichiometric composition of such formulations on the final binder's phase composition is not widely reported. Especially the influence of short heat treatments to the binder paste, to trigger an immediate setting reaction, on their phase development, was never before reported. This research will help to better understand downstream binder properties like mechanical strength and water resistance, by knowing their phase compositions, of this critical material class for a more sustainable future.

Methodology

Magnesium oxychloride cement formulations of different molar compositions were produced from magnesium chloride hexahydrate, tap water and a source of reactive magnesium oxide (half-calcined dolomite and caustic calcined magnesium oxide (CCM) from magnesite). Half-calcined dolomite was either used as sole source of magnesium oxide, or mixed with CCM to obtain a 1:1 molar mixture. The base molar ratio of $MgO:MgCl_2$ was either 5:1 or 6:1. The effective ratio was slightly changed by taking into account the magnesium oxide source's purities (based on XRF data), as well as their activities, as determined by the WB/T 1019-2002 standard method. The water to $MgCl_2$ ratio was kept constant at 17:1, to ensure a good paste workability. The pastes where then heated to different temperatures between 50 and 100 °C for several minutes, or left at room temperature. Directly after the heat treatment, the samples were characterized by XRD over time. Measurement intervals changed from 2 hours within the first 24 hours to longer intervals up until 2 weeks, where the phase composition typically stabilized. The mineral phase composition was calculated from the diffractograms for each time step of each formulation. Using the known starting composition of all formulations and the theoretical final composition, respective binder phase (phase 5, the most desired cement phase) conversion and the share of unreacted MgO were calculated, as well as an estimate of the amorphous content through the inherent calcium carbonate (calcite) marker.

Results

All investigated formulations and heat treatments showed a conversion of the periclase (magnesium oxide) phase into other magnesium phases over time, usually approaching an equilibrium composition after ca. two weeks. At room temperature, i.e. without thermal activation, periclase directly converted to phase 5, starting after around 4 hours after mixing. Within these 4 hours, the calculated amorphous content is substantial (20-40 wt%). Phase 5 conversion degrees of 80-90% were usually achieved after two weeks, while typically 20% of magnesium oxide remained unreacted. Correcting the magnesium oxide content by purity and activity did not significantly increase the binder conversion degrees, but increased the share of unreacted periclase. This indicates that the conversion limiting factor is not the amount of reactive magnesium oxide in the formulation, but its availability for the reaction, e.g. limited by diffusion, so ultimately by particle size.

Thermal activation lead to the formation of significant amounts of bischofite (magnesium chloride hexahydrate) in some formulations. Bischofite formed within a few hours, but transformed to phase 5 within several days. Heat treatments at 80 °C and above, where the binder sets within minutes, lead to major phase composition changes in all formulations. Immediately, large amounts of brucite (magnesium hydroxide) were present. Depending on the formulation, phase 5 was still formed with a few or several days of delay. However, even after two weeks, the brucite content was still at 10 to 20 wt% and conversion to phase 5 almost stopped.

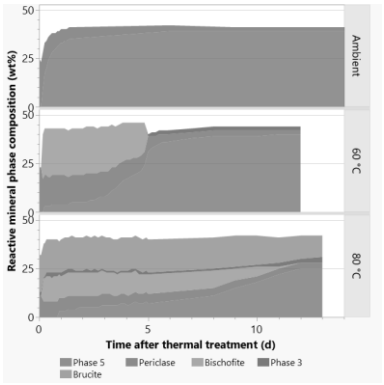

Figure1: Kinetic mineral phase development of a 100% half-caclined dolomite based formulation with a 6:1:17 MgO source/magnesium chloride/water stoichiometry, depending on the thermal treatment temperature.

Conclusion

This work shows, that it is possible to produce MOC from half calcined dolomite and mixtures with caustic calcined magnesium oxide, achieving conversions into binder phase at high levels. Further optimisation of binder conversion likely requires finer particles and cannot simply be achieved by changing the formulation parameters. Desirable fast setting can be achieved with mild heat treatments to the cement paste for only some minutes. However, these significantly impact the transient and final cement phase composition. Temperatures around 80 °C are critical, since significant amounts of brucite are formed, that likely explain detrimental effects on strength and water stability that are commonly reported. This work shows the critical value of XRD investigation to better understand the behaviour of MOCs under real world conditions. Further work is needed to better understand the underlying mechanisms for the observed mineral phase formations.

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Thermodynamic Modelling Approach for the Processing of Low-Temperature Belite Cement Clinker from Concrete Waste Using Na_2CO_3 & $CaCl_2$ as Mineralizers

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Keywords: Concrete Recycling, CO_2 Reduction, Low-Temperature Belite Clinker, Thermodynamic Modelling

Introduction

In this study, we are researching the processing of belite (Ca_2SiO_4) cement clinker from the cementitious waste at lower temperatures, i.e. at 1000°C using a mineralizer in a CO_2 atmosphere. Belite clinker is based on a lower CaO/SiO_2 molar ratio (2 instead of 3) compared to Ordinary Portland Cement Clinker. As a result, less $CaCO_3$ is required as a CaO source, significantly reducing CO_2 emissions. The low-temperature process allows complete electrification and results in a pure CO_2 kiln atmosphere which facilitates subsequent sequestration. Beyond understanding the reaction pathways for this new process, the main challenge is the variable chemical composition of the cementitious wastes. As a consequence, product composition is significantly affected, yet exploring the products for every changing raw material experimentally is a time-intensive process. Therefore, we perform thermodynamic modelling to understand the compositional effects, reaction pathways, phase transformations and contribute to process optimization.

Methodology

In the experimental approach first, concrete waste is crushed, which yields fine and coarse fractions. The fine fraction which is enriched in cement paste is used as a raw meal component. Next, the chemical composition of cementitious fines is analysed and the required amount of $CaCO_3$ is added to adjust the CaO/SiO_2 molar ratio to 2. Additionally, 2-5 wt.% of mineralizer either Na_2CO_3 or $CaCl_2$ is added which aids in the formation of a partial melt during the process. Later, the raw meal is heated in a rotary kiln to obtain belite cement clinker, followed by phase analysis.

FactSage Software along with its databases is used in the modelling approach. It is important to ensure that the thermodynamic data of all phases that can occur in the system are present in the database. While the standard FactSage database has well-optimized data for most of the oxide systems, it still lacks data for some of the typical phases that occur in the belite process. Therefore, the missing data are identified and added to the database from the literature. However, sometimes, contradictory data may be found, which requires careful evaluation. Later, the input parameters for the calculation are defined. Simulations are performed at different temperature steps to calculate equilibrium phase assemblages and generate phase diagrams. Finally, the results are validated with the experiments.

Results

Impact of the mineralizer: Concrete waste composition varies depending on the source, with CaO and SiO_2 as major components. Other oxides, including aluminium, iron, alkalis, and sulphates are also present depending on the cement types and concrete mix designs used. One among them is Autoclaved Aerated Concrete (AAC), which contains higher sulphate levels compared to standard concrete waste. The high sulphate content restricts landfill options, making AAC an important material for recycling. The

experimental and simulation results of belite clinker from both wastes (standard concrete and AAC) with 5 wt.% of Na_2CO_3 show belite as the main phase. The main difference between the two clinkers is the formation of the Na_2SO_4 phase in a high-sulfate sample, which is undesirable since it dissolves in water during hydration. To address this issue, $CaCl_2$ is used as a mineralizer, which leads to the formation of the insoluble mineral chlorellestadite ($Ca_{10}(SiO_4)_3(SO_4)_3Cl_2$) where chlorine and sulphate are fixed. As both experiments and simulations confirmed the presence of chlorellestadite, $CaCl_2$ is used as the mineralizer for the samples with high sulphate content.

Detection of melt formation: The main difference is that the simulations show a melt phase at 1000°C with mineralizers, while experiments always show amorphous content after cooling. The amorphous content could be due to grinding before Rietveld analysis or from uncrystallised melt. Validating the melt phase is challenging, as in-situ XRD detect only crystalline content. Simulations show a melt phase only when a mineralizer is present. In experiments, adding a mineralizer increased belite turnover, which indicates the presence of melt at high temperatures.

Impact of reaction kinetics: Additionally, the experiments show unreacted starting materials ($CaCO_3$, SiO_2) and non-equilibrium phases such as CaO and wollastonite ($CaSiO_3$) which could be due to particle size, and inhomogeneity. However, by simulating ternary phase diagrams, varying the major components at the vertices of the triangle and fixing the compositions of the minor components it is possible to predict the phases under local equilibrium conditions.

Conclusion and Outlook:
Thermodynamic modelling provides important insights into phase evolution, the role of mineralizers in melt formation and also the effect of compositional variations on the product. The simulations with the mineralizer indicate a melt phase at higher temperatures. Additionally, the experiments show increased belite turnover with mineralizers. Hence both the results highlight the influence of mineralizers. In future work, additional analytical techniques will be used to identify the melt for thermodynamic model validation, with data optimization if needed. Finally, the conditions under which the thermodynamic model of the belite can be applied along with limitations will be studied.

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Toward understanding the role of magnesium salts in alkali-free accelerators in controlling the setting and hardening of accelerated cement pastes

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Keywords: shotcrete, accelerator, magnesium, setting and hardening

Aluminnum sulfate-based alkali-free accelerators have been increasingly prevailing in modern shotcrete production due to their minimal environmental impact, reduced risk of alkali-aggregate reaction, and negligible effects on long-term strength and durability. However, the mechanism of impacts of magnesium salts, as one of key components in liquid alkali-free accelerators, on the setting and hardening of accelerated cement pastes remains poorly understood. To this end, this study prepared aluminium sulfate-based accelerators containing different magnesium salts (including $MgSO_4$, $MgSiF_6$, and $Mg(NO_3)_2$), and systematically compared their effects on setting and early-age properties of cement pastes. The setting behaviours, early-age mechanical properties, hydration kinetics, and microstructure were thoroughly evaluated by isothermal calorimeter, SEM, XRD, ^1H NMR etc. And the morphology of ettringite and the percolation was computed by a hard-core-soft-shell model to further reveal the relationship between ettringite and setting behaviours. The main conclusions drawn from this study include:

(1) The inclusion of magnesium salts reduced the pH of the aluminium sulfate-based accelerators, the degree to which was dependent on the type and amount of magnesium salts. Generally, higher dosage of magnesium salts corresponded to a lower pH. Among the magnesium salts studied, the most significant drop in pH came from $MgSiF_6$, followed by $Mg(NO_3)_2$ and $MgSO_4$, respectively.

(2) Magnesium salts in aluminium sulfate-based accelerators played a crucial role in the setting and hardening of cement pastes. Regardless of the specific magnesium salt, it tended to shorten the initial setting time with the higher dosage producing a more pronounced effect. Notably, $MgSiF_6$ remarkably reduced the initial and final setting times, $MgSO_4$ reduced the initial setting time, and $Mg(NO_3)_2$ slightly improved the initial setting time. Regarding mechanical properties, both the 6 h compressive strength and flexural strength were significantly weakened by $MgSiF_6$. On the contrary, $MgSO_4$ promoted the compressive strength at the optimal dosage of 5% while reducing the flexural strength. $Mg(NO_3)_2$, however, promoted both the 6 h compressive strength and flexural strength.

(3) $MgSiF_6$ obviously inhibited C_3S hydration, prolonging the induction period. Additionally, it increased the porosity of hardened cement pastes hydrated for 6 h, which was the main cause of the weakened mechanical properties at this time. Nevertheless, both $MgSO_4$ and $Mg(NO_3)_2$ enhanced C_3S hydration and further refined the microstructure, accounting for the improved 6 h compressive strength.

(4) The formation of ettringite in accelerated cement pastes occurred rapidly, irrespective of the type of magnesium salts, reaching dimensions of 0.08~0.16 μm in width and 0.35~0.8 μm in length just within several minutes with minimal further growth at later ages. $MgSiF_6$ contributed to a faster formation of ettringite at the early age and increased its width and length, leading to a high aspect ratio. This is favourable for the particle overlap and thus forming a percolation, which in turn promoted the setting of cement pastes.

(5) The low pH environment of $MgSiF_6$ may help to induce the incorporation of magnesium and fluoride into ettringite, potentially explaining the change in morphology and reduced thermal stability of ettringite. In contrast, $MgSO_4$ and $Mg(NO_3)_2$ had few effects on the morphology as well as chemical composition of ettringite. Further research is needed to provide more evidence and elucidate the mechanisms behind these changes in ettringite's chemical composition and morphology.

The findings reported in this study advance our understanding of setting and hardening mechanisms in accelerated cement pastes and offer valuable guidelines for optimizing accelerator formulations.

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Preliminary Studies on Biochar Concrete – An Alternative to Cement

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Keywords: Biochar, Cement replacement, Optimization, Mixes, Strength & workability

Biochar is classified as biomass ashes from plant shrubs or trees which can be utilised for material replacement in cements. Biochar reduces the significant CO2 emission associated with cement productions and acts as carbon sinks. The present study, utilizes biochar in the replacement of 1.5%, 4%, 6.5% of cements and optimizes the mixes for better mechanical and durability properties. Different types of mixes were adopted to prevent water-sogging and uneven dispersion of biochar in cement matrix. Ball milling were done on procured ashes after pyrolysis process to prevent the unevenness in ash and easy use in mixes. After ball milling biochar ashes were oven dried to remove any inbuild water present, making it suitable for batching. While mixing care was done, to avoid any lumping of ashes with cement powders and finally wet mixed with water. Observed results shows that; wet mixing of biochar performs well in comparison to dry mixing and compressive strength of 1.5% replacement of cements with biochar performs wells; whereas higher replacements of cements by biochar reduces the strength due to associated water sogging of the material. To improve water-resistance of biochar, pre-treatments were performed with heat resistance and this helps to increase the mechanical property. Workability decreased with increase in % of biochar and compaction has to be done to improve the workability. Shrinkage properties decreased with increase in % of biochar, making the samples highly susceptible to voids and pores. Even pre-treating the biochar mixes couldn't perform well. Although carbon storage can be improved with use of biochar in concrete, in depth analysis and carbon capture calculations has to be done based on the embodied carbon associated with ash and cement binding. Energy calculations although show less carbon associated with biochar their applicability has to be understood further for civil infrastructures. Further, these new green materials have to be studied exclusively to obtain better performances with desired results in cement mixes. With improvements in biochar standardisation and mixing strategies, applicability of these biomass ashes can be increased.

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Use of carbon dioxide mineralisation of granite powder waste as a sustainable method for partial replacement of cement

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Keywords: cementitious composites; mineralisation; quarry waste; zero-net emission

The amount of post-mining waste is increasing year on year in every country of the European Union. The lack of industrial use is influencing the accumulation in heaps of waste resulting from the crushing or cutting of granite rock. This affects the environment, reducing natural habitats for animals, pollinating plants or leading to landslides and sinkholes. Granite dust carried by the wind can also cause pneumoconiosis or respiratory diseases in humans. This problem has also been recognised by the European Union, which has introduced a policy aiming to increase the re-use of quarry waste. One of these ways is to use it in concrete. Unfortunately, according to studies, granite powder waste without prior valorisation will not allow a significant (+10%) replacement of cement in concrete, and its impact is limited to the so-called filler effect. It seems that an interesting method to increase the utilisation potential of granite powder waste in concrete could be its mineralisation of carbon dioxide (CO_2). Mineralisation in an aqueous medium (calcium hydroxide) allows the formation of a calcium carbonate coating on the surface of the granite powder particle, which then influences the hydration reaction of the cement allowing a faster development of compressive strength. The simplicity and significant environmental impact (CO_2 utilisation) of the method have led to intensive research being carried out on this method with a view to industrial implementation of this technology in the manufacture of cementitious composites.

In our research, we used the method of direct CO_2 mineralisation in an aqueous environment of granite powder waste to replace 10, 20 and 30% of cement in concrete. From the mineralised granite powders (MGP), we made concrete and investigated fresh mix (slump flow, bulk density, heat of hydration), mechanical (compressive and tensile strength, nanoindentation of the interfacial transition zone surface - ITZ) and microstructural (SEM, XRD, TGA) tests. We performed also Life Cycles Analysis (LCA).

We observed that the CO_2 mineralisation of granite powder alters the grain surface structure, forming calcium carbonate crystals on the surface in the form of aragonite. Replacing the cement with the addition of MGP slightly reduced the spreading of the mixture, increasing its bulk density and reducing the heat of hydration of the cement. Replacing 20% of the cement with MGP led to a 15% increase in mechanical properties compared to the series modified with GP. Finally, we observed changes in the microstructure of the composite, due to reduced porosity in the ITZ and the composition of the mineralogical composition of composites.

The results indicate a great potential of the method of mineralization of quarry wastes for their reusing in the cementitious composites industry. This will reduce the environmental footprint of construction and limit the energy consumption of building materials due to the reduction of cement content in concrete. In conclusion, the mineralization method of GP used allowed the waste to be transformed into a product that will be highly desired by the industry. The method used allowed for the permanent binding of 6 g of calcium carbonate on the GP surface for every 100 g of GP, reducing the emission of the concrete mix by up to 66% (replacing 30% of cement with the addition of mineralized GP). MGP influenced the ITZ by allowing for a reduction in the porosity of the aggregate-cement matrix connection zone and allowing for the production of a greater amount of the main cement hydration products.

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Using Thermodynamic modelling to Calibrate Phase Quantification in *In-Situ* XRD Analysis of Pb-containing Hydrating Cement

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Keywords: Geochemical modelling, Heavy metal, Hydration kinetics, Portland cement, Pb.

Pb-induced retardation effects on cementitious materials have been widely reported. Understanding the role of Pb in hydration kinetics is fundamental for scaling up the utilization of Pb-containing by-products as additives in the cement industry and for advancing solidification/stabilization applications for Pb-bearing solid wastes. Recently, *in-situ* laboratory X-ray diffraction (*in-situ* XRD) has been proposed as a semi-quantitative method for phase analysis of hydrating cement pastes. This approach provides an ideal way to link phase development in cement pastes to hydration kinetics without affecting the process. However, the presence of amorphous or non-crystalline phases makes fitting *in-situ* XRD patterns challenging due to the lack of a well-defined crystal structure. In particular, investigating calcium silicate hydrate (C–S–H) through XRD is difficult because C–S–H in cementitious pastes lacks long-range atomic ordering and does not produce distinct Bragg reflections like crystalline materials. Moreover, amorphous C–S–H is a predominant hydration product in ordinary Portland cement, and its precipitation may be significantly retarded by Pb incorporation but cannot be directly observed. To address this limitation, we employed a thermodynamic model to calibrate phase quantification results from *in-situ* XRD with mass balance calculations.

In this work, the hydration process of ordinary Portland cement blended with anglesite (PbSO4) under ambient temperature were investigated by *in-situ* XRD and *ex-situ* X-ray powder diffraction (*ex-situ* XRD). The blended powder samples were mixed with deionized water under a water-to-solid ratio of 2.45 and a mixing speed of 200 rpm. To determine the dissolution kinetics of clinker phases, we calculated the scale factors of the cement phases from *in-situ* XRD patterns and refined the relative quantification results from *ex-situ* XRD patterns. The evolution of clinker phase contents revealed that the addition of anglesite significantly retarded the hydration process and the precipitation of portlandite and ettringite. Measured heat of hydration curves using isoperibolic calorimetry show a strongly retarded rate of cement hydration in the presence of anglesite. Additionally, scanning electron microscope and energy dispersive spectrometer analysis suggest that Pb is well dispersed within the cementitious matrix. Afterwards, we employed

PHREEQC V3 develop a thermodynamic model for calibrating the phase quantification results and estimating the amount of amorphous C–S–H. Two thermodynamic databases, CEMDATA18.DAT and PHREEQC.DAT, were utilized. The initial inputs of the thermodynamic model were derived from cement phase contents determined by *in-situ* XRD and *ex-situ* XRD analysis. Further, the isoperibolic calorimetry was used to calibrate the amount the clinker phases dissolved. The results suggest that

Overall, these findings provide new insights into Pb-induced retardation effects to cement hydration and establish a probability for optimizing the reuse of Pb-bearing industrial by-products in cementitious materials. The integration of experimental analysis and thermodynamic modelling provided a comprehensive understanding of Pb-induced retardation effects in cement hydration. The combination of *in-situ* XRD, *ex-situ* XRD, and isoperibolic calorimetry enabled the semi-quantification of phase evolution and clinker dissolution kinetics. The thermodynamic model further improved phase quantification accuracy, particularly for poorly-crystalline C–S–H. Although the hydration process of Pb-incorporated mixtures can be modelled, our understanding of the complex interactions between pore solution composition and dissolution kinetics remains insufficient for accurately predicting the hydration kinetics of the blended systems. While initial attempts with simplified systems have proved promising, a more comprehensive thermodynamic database for Pb-bearing minerals in cementitious systems is still needed.

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Utilization of Recycled Concrete Waste in the Production of Zero-Slump Concrete

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Keywords: Zero-slump concrete, Recycled concrete aggregates, Recycled concrete fines, sustainable concrete, low CO2

Zero-slump concrete is a dry concrete mixture characterized by its extremely low water content, resulting in a stiff and non-flowable consistency. Unlike conventional concrete, which depends on workability for placement and compaction, zero-slump concrete requires external mechanical force, such as pressing or vibration, to be shape. This unique characteristic makes it particularly suitable for precast elements such as paving blocks, structural bricks, and other modular components. In parallel with performance optimization, the integration of recycled materials into concrete production is becoming increasingly relevant as the construction industry moves toward more sustainable and resource-efficient practices. Recycled concrete aggregates (RCA) and recycled concrete fines (RCf) are byproducts generated during the crushing and processing of demolished concrete structures. RCA has been widely studied as a substitute for natural coarse aggregates in various applications, offering benefits such as reduced environmental impact conservation of raw materials, and minimized carbon footprint. Studies have demonstrated that, with appropriate processing and mix design adjustments, RCA can be effectively used in conventional concretes with minimal compromise to performance. However, RCf, in particular, is still predominantly landfilled, despite its potential as a fine filler material. Due to its finer particle size and higher surface area, RCf poses challenges related to water demand and workability in conventional concrete. Nevertheless, in low-workability systems such as zero-slump concrete, these characteristics can be leveraged to improve particle packing, reduce porosity, and enhance compressive strength when properly incorporated into the mix design.

Thus, this study investigated the development of a zero-slump concrete incorporating RCf and RCA, with a primary focus on enhancing compressive strength through optimized mix design. The aim was to achieve a dense particle packing structure that maximize the compactness of the final block. The recycled materials used in this research were supplied by a recycling facility in the Netherlands. Further, the concrete waste were processed through controlled crushing and sieving using a Smart Crusher in the laboratory to obtain the desired RCA and RCf fractions. The experimental program was carried out to evaluate the physical and chemical properties of the recycled constituents initially, by X-ray diffraction (XRD), X-ray fluorescence (XRF), particle size distribution (PSD) analysis, and density measurements. Ordinary Portland cement (OPC) was used as the binder, and a particle packing model was adopted to design target gradation curves. Concrete blocks were then produced by varying parameters such as water-to-cement (w/c) ratio and particle size distribution. These variables were adjusted to assess their influence on mechanical behaviour and early-age performance. Zero-slump concrete is often demoulded and handled shortly after pressing, early-age strength is a important performance indicator. Therefore, compressive strength tests were conducted at both 24 hours and 28 days. All samples were cured in a climate chamber under controlled environment to ensure consistent hydration and minimize external variability. The results provide valuable insights into how material composition and pressing behavior influence the pore structure and strength of zero-slump concrete. This work contributes to the growing of knowledge on recycled building materials and supports the shift toward a circular construction economy by offering a viable application for demolition waste.

Utilization of Sugarcane Bagasse Ash as a Sustainable Supplementary Cementitious Material: Processing, Performance, and Applications

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Keywords: Sugarcane bagasse ash, Pozzolanic materials, Supplementary cementitious material, Strength activity index, Modified Chapelle tests.

Abstract

Sugarcane bagasse ash (SCBA), a byproduct of the sugar industry, has gained significant attention as a potential supplementary cementitious material (SCM) in sustainable construction. The increasing demand for eco-friendly and cost-effective alternatives to traditional cement has driven research into utilizing industrial byproducts, such as SCBA, to enhance the performance and sustainability of cement-based materials. SCBA is rich in silica and other pozzolanic compounds, which contribute to improved cement hydration and strength development when used as a partial replacement for cement. However, its effectiveness as an SCM depends on several factors, including its chemical composition, particle size, loss on ignition (LOI), and the pretreatment methods employed to optimize its reactivity. This study explores the characteristics, processing techniques, and performance evaluation of SCBA in cement-based applications. The raw SCBA, as collected from sugar industries, often contains high carbon content and unburnt residues, which can negatively impact its pozzolanic properties. Various pretreatment methods, including controlled burning, grinding, and chemical activation, have been proposed to enhance its reactivity and ensure compliance with industry standards such as ASTM C618. Thermal treatment at optimal temperatures (typically between 600°C and 800°C) significantly improves the silica crystallinity and reduces the carbon content, leading to enhanced pozzolanic activity. Additionally, mechanical grinding refines the particle size distribution, increasing the surface area and improving its reactivity with calcium hydroxide ($Ca(OH)_2$) during cement hydration.

The pozzolanic reactivity of SCBA is assessed through strength activity index (SAI), modified Chapelle tests, and other pozzolanic evaluations. Research indicates that SCBA can replace up to 10–20% of cement in concrete mixes without compromising mechanical and durability properties. The incorporation of SCBA enhances long-term compressive strength, reduces permeability, and improves resistance to sulfate attack, chloride penetration, and alkali-silica reaction (ASR). Additionally, the high specific surface area of processed SCBA contributes to improved particle packing, reducing porosity and enhancing microstructural properties. Despite its promising attributes, the large-scale utilization of SCBA in cementitious materials faces challenges related to variability in its composition, water demand due to its high LOI, and the need for consistent pretreatment methods. To address these challenges, further research is required to develop standardized processing techniques and establish guidelines for its optimal use in cement-based products. The synergistic use of SCBA with other industrial byproducts, such as ground granulated blast furnace slag (GGBS) and fly ash, could further improve its performance and broaden its applicability in sustainable construction.

The adoption of SCBA as an SCM offers multiple environmental and economic benefits. It reduces the carbon footprint of cement production by lowering clinker consumption, minimizes waste disposal issues in sugar industries, and promotes a circular economy by utilizing industrial byproducts effectively. Furthermore, SCBA-based cementitious materials exhibit potential for application in low-cost housing, high-performance concrete, and durable infrastructure. Sugarcane bagasse ash demonstrates significant potential as a sustainable supplementary cementitious material when properly processed and utilized. Future

research should focus on refining processing techniques, establishing industry standards, and conducting large-scale field applications to fully realize its benefits. Integrating SCBA into cementitious systems aligns with global efforts toward sustainable construction and carbon footprint reduction, making it a valuable alternative in the transition to greener building materials.

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Valorization of calcite rich residue fro0m basic oxygen furnace slag in sustainable clinkers and supplementary cementitious materials

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Keywords: Calcite rich residue, Basic oxygen furnace slag, Recycling, Clinker, Supplementary cementitious materials

Portland Cement (PC) is one of the most important building materials, playing a significant role in the built environment. With population growth and increasing demand for new infrastructure, the production and use of PC have exceeded 4 billion tons annually, raising concerns about sustainability. At the same time, a wide range of industrial residues are being generated, many of which have potential for upcycling in construction. For example, the metallurgy industry produces various slags that need to be recycled due to environmental and circular economy concerns. Some of these residues, such as ground granulated blast furnace slag, have been extensively studied and are now commonly reused in the construction industry.
However, as the steel industry shifts toward more sustainable production methods, new types of slag—such as basic oxygen furnace (BOF) slag—are being generated. There is currently limited research on the potential for reusing these newer steel slags. This study investigates the potential of using a calcite-rich residue from BOF slag as a Supplementary Cementitious Material (SCM) and as a limestone substitute in clinker production.
The prepared binders were characterized for their fresh and hardened properties using various techniques, including isothermal calorimetry, rheology, setting time, compressive strength testing, X-ray diffraction (XRD), thermogravimetric analysis (TG/DTG), and Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). Reference compositions without residues were also prepared for both clinker and SCM evaluations.
The results showed that typical phases of Portland cement—alite, belite, aluminate, and ferrite—were present in comparable amounts in both the reference and the residue-containing clinker. Alite exhibited a higher phase purity compared to belite, ferrite, and aluminate, which appeared to incorporate more impurities. Microstructural analysis of both cements revealed substantial amounts of portlandite (CH) and calcium silicate hydrate (C-S-H) gel, along with some relics of unreacted belite. TG/DTG analysis confirmed CH and C-S-H as the main hydration products, along with monosulfate/ monocarbonate phases, with mass loss increasing over time due to continued hydration.
Leaching of vanadium (V) and chromium (Cr) from mortars made with the residue-based cement was negligible, indicating the material's environmentally friendly nature. Furthermore, the mechanical properties were comparable to those of mortars made from both the reference cement and commercial CEM I, with 28-day compressive strength reaching approximately 55 MPa. This suggests strong potential for upcycling the calcium-rich stream as a feedstock for the Portland cement industry.
The practical reuse of this residue stream not only supports circular economy goals but also reduces environmental impact and energy consumption associated with mining natural limestone for cement production. Clinkering experiments indicated that up to 11 wt.% of the calcium-rich stream can be

incorporated into the clinker raw mix—equivalent to 9 wt.% limestone substitution—without significant changes in cement chemistry or mineralogy.
Additionally, when used as a supplementary cementitious material, the residue reduced workability due to its fine particle size (median ~2 micrometres). However, preliminary 3D printing tests showed that this fineness improved the printability of concrete. Overall, the results demonstrate significant potential for reusing BOF slag and similar residues in the production of sustainable cement and concrete.

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Valorization of subproduct-clay from Cementir Holding by Mechano-chemical activation

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Keywords: Activated clay, Quartz-rich clay, R3 reactivity test, Mechano-chemical activation.

The cement companies are under a high scrutiny looking to find the NET-ZERO for 2050. This NET-ZERO is searching to decrease and/or eliminate amount of CO2 emitted during its production process. This includes from extraction of raw materials up to the final product cement and concrete (three different scopes). It is known that a production of 1 ton of Ordinary Portland clinker, emits around 850 kg of CO2; representing around 4-5 % of CO2 man-made. CEMBUREAU has proposed an ambitious NET ZERO roadmap for European Cement Companies. They have proposed the reduction in the 5 stages of the cement value chain (5Cs: clinker, cement, concrete, construction, carbonization). Where the main contribution is expected to be from 3 main fronts: clinker, CCUS and cement. In the case of clinker, the CO2 emission is focused on decarbonated raw materials, low carbon clinker, alternative fuels and thermal efficiency. While in the case of cement is focused on clinker substitution, electrical efficiency, carbon neutral cement transport. Giving one of the main focuses to cement producer on clinker substitution. Between the clinker substitutions alternatives, we could find several SCMs, where slags and fly ashes are well known, but they availability is decreasing due to improvements on steel and electricity production, respectively. Another SCMs well known are the natural pozzolans, which are difficult to find with a significant pozzolanic reactivity than slags or fly ashes. Around 15 years ago, there is a revolution based on the use of thermal activated clays, which are quite abundant around the earth. Considering them as a promising alternative for clinker substitution in a cement, even though as concrete addition. The synergy found between the thermal activated clay and limestone, has give a milestone in the cement production. Where Cementir Holding launched to the market for first time a cement constitutes by thermal activated clay, limestone and clinker. This product is recognized as FUTURECEM® in Nordics and Benelux countries. Usually, the thermal activated clays projects are focused on kaolinitic clays, which should have at least 25-30% of this mineral to be correctly activated and considered as SCMs. But this type of clay is very rare inside European countries, where we can find quartz-rich, calcite-rich, pyrite-rich, smectite/illite-rich clays; which after thermal treatment are much less reactive than the clays with significant amount of kaolinite. In 2024, Thyssen-Krupp launch a technology based on use of high energetic grinding systems to activate clays without the use of heat treatment (known as calcination). This technology has a deep background on several research done about the use of mechano-chemical activation of different minerals for different purpose apart from cement industry. One of the well know is the one done by I. Tole and V. Ronin, and in the recent years by S. Bernal and A. Marsh. Based on these results, in GRQCC of Cementir Holding had decided to study how this could be done inside our laboratories in RQC. For the study, one of the subproduct clays from one of the cement companies of the Holding were selected. All the general characterization by TGA, XRF and XRD was done before and mechano-chemical activation. The mechano-chemical was carried out in 500 mL planetary ceramic ball mill, with ceramic grinding media of 20 mm diameter, using a ball/powder ratio of 10 and 25 and rotation speed of 500 rpm for 20 and 40 min. After the mechano-chemical activation, the samples were characterized by XRF, XRD, SEM, R3 reactivity test and Activity index (with a 25% of CEM I 52.5N replacement) for the most promising sample. All of these were compared with the same subproduct clay activated by flash calcination. The results have shown that the mechano-chemical activation brings higher pozzolanic and latent reactivity than the same sample activated by flash calcination.

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Volume 1

Section 1.5: Concrete technology, Recycling and Circular Construction

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A case study of residential construction waste generation in New Zealand

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Keywords: Sustainable construction; residential buildings; construction waste assessment; circular economy

Construction waste is a worldwide issue that is increasing. Almost half the material extracted from this planet is converted into buildings, but the construction industry suffers from high waste levels. Construction and Demolition (C&D) waste was reported as the third largest waste stream worldwide, following municipal solid, and commercial and industrial waste. Worldwide, it is estimated that between 16 and 60% of landfill waste is generated by the C&D sector. In higher-income countries which are members of the Organisation for Economic Co-operation and Development, C&D waste was the largest waste stream. This indicates that, as income increases in a country, quantities of C&D waste also increase.
Worldwide, it is estimated that between 16 and 60% of landfill waste is generated by the C&D sector. In countries with building systems similar to New Zealand (NZ), the landfill rate is 33% (USA), 35% (Canada), 50% (UK) and 20-30% (Australia). Residential dwellings predominate the construction sector in NZ with 88 % of all new buildings by quantity, 75 % by value, and 71 % by floor area, therefore residential dwellings prevail in C&D waste generation. NZ generated 3.6 million tonnes of C&D waste which accounted for half of total landfill waste.
This rate of C&D waste disposal created negative environmental impacts, and economic concerns for local councils and industry practitioners. This concern was further exemplified in a survey conducted by the Ministry for the Environment in which waste was the second equal ranked issue facing the country over the next two decades after poverty reduction.
The case study consisted of two 3-bedroom units, and a 4-bedroom unit within a larger ten-unit project. It includes multiple data collection and analysis methods:

- Document Analysis- Architectural plans, Bill of Quantities, waste reports from collectors, etc.
- Site Visits- 60 site visits were conducted over a period of 20 weeks which covered the period from foundation to house fit off.
- Image Analysis- A total of 1180 images were taken, out of which 786 images targeted waste bins
- Discussion with Project Manager- discussion helped to understand real-time site conditions and encompassed missing aspects of design and execution
- On-site observations- it helped to understand the process (or behaviour) and its impacts.

Findings showed that, over the three units an average of 22.7kg/m2 of waste was generated, without decking, landscaping and fencing. In total, 18 waste streams were identified and quantified. The three most prominent waste streams accounting for 87% of total waste were timber (44%), plasterboard (28%) and metals (15%). All other materials accounted for less than 3% each. There were four learnings from the project:

- Future builds would be easier to analyse if all construction on a site was included in monitoring and interventions applied to the whole site.
- There needs to be a chain of custody system for waste to allow for correlation between observation onsite and measurement at the resource recovery centre.
- Visual images provided a very useful guide to demonstrate to stakeholders how and what waste accumulated.

- Recognition of attributing waste to build stage to give a record of hot points and stages of wasted material generation.

A Life Cycle Decision Support Framework for Optimal Sludge-Driven Construction Material Selection- A Waste to Wealth Approach

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Keywords: Life cycle decision support framework, Sludge management, Brick manufacturing, Construction material selection, Life cycle analysis.

Abstract
The growing global emphasis on sustainable construction practices has catalyzed the search for innovative materials that minimize environmental impact while enhancing performance. Sludge, as a waste material, is responsible for a significant portion of global carbon emissions and environmental pollution. Novel progress in materials science has enabled the reuse of waste materials for the fabrication of construction materials. This study explores how the performance of the waste materials-driven construction materials can be evaluated based on life cycle data, which is crucial for practical implications. For this purpose, this study proposes a novel life cycle decision support model that considers social, environmental and technological aspects to select the optimal construction materials based on life cycle experimental data.

To develop this model, we proposed a robust, novel life cycle decision support framework that integrates the advanced fuzzy best worst method with advanced fuzzy TODIM (TOmada de Decisão Iterativa Multicritério) to evaluate the performance of sludge-driven construction materials, taking into account environmental, technical, and social life cycle data. Life cycle data were gathered from an extensive literature review regarding sludge used in construction material preparation. This included the physical and chemical properties of various construction materials prepared from different types of waste sludge. To facilitate decision-making, we employed an advanced fuzzy best worst method integrated with an advanced fuzzy TODIM multi-criteria decision analysis (MCDA) framework, which considers diverse factors such as environmental, social and technological performance with material availability. This approach allows stakeholders to weigh different parameters according to their specific priorities and constraints. A sensitivity analysis was conducted to evaluate how variations in key input parameters affect the model's outcomes. This step is crucial for understanding the robustness of the model and identifying the most influential factors in the decision-making process.

The results of this study indicate that the life cycle decision support model can robustly identify the importance of the performance evaluation criteria and the optimal sludge-driven construction material. The findings indicated that the two most important performance evaluation criteria are "Compressive strength" and "Firing energy saving" and the best performed construction material is "bricks manufacturing from tannery sludge where 10% tannery sludge combined with clay" which outperformed the combinations of 10% textile, sewage and arsenic-iron and tannery sludge in ceramic tiles. This indicates that stakeholders can select the most appropriate sludge-driven construction material for practical application in the construction industry, as the proposed model can evaluate the social, environmental, and technical aspects of the construction materials.

This life cycle decision support model represents a significant advancement in the field of sustainable construction materials. By preparing construction materials from sludge, we can address critical issues related to waste management, resource efficiency, and carbon emissions. The model serves as a practical tool for stakeholders in the construction industry, enabling informed decisions that align with sustainability objectives.

Future research should focus on scaling up the applications of sludge in brick manufacturing by developing a specific LCA model to extract the data for in-depth cradle-to-cradle life cycle analysis. Additionally, policy frameworks that support the adoption of waste sludge in construction can further drive the transition towards sustainable building practices. Overall, this study underscores the transformative potential of waste sludge as a sustainable alternative in building materials fabrication, paving the way for a more sustainable future in the construction industry.

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A study on two methods to strengthen cement-based materials

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Keywords: cementitious materials, strengthening, carbonation, phosphate, hydroxyapatite

Cement-based materials are fundamental to modern infrastructure and the built environment, owing to their versatility, durability, and widespread availability. However, the production of cement is highly resource-intensive, requiring vast quantities of natural resources, such as limestone and clay, while simultaneously generating significant carbon emissions. Given the immense global demand, the cement industry alone is responsible for approximately 5–10% of total global CO_2 emissions, making it one of the largest industrial contributors to climate change. In response to these critical challenges, substantial efforts have been directed toward reducing the high carbon footprint in the cement and concrete industry. Various mitigation strategies have been explored, including, e.g. enhancing cement manufacturing efficiency, incorporating greater proportions of supplementary cementitious materials (SCMs) such as fly ash and slag as partial cement replacements, optimizing structural design to minimize material usage while maintaining performance, and extending the service life of concrete structures. Of the various strategies proposed, optimized use of cement in concrete (or minimizing the cement content) has attracted significant interest. More recently, the direct reuse of structural concrete elements and components has emerged as another promising method, garnering increased research attention. These strategies have huge potential to substantially reduce the overall environmental impacts of the construction industry. However, for the strategies to be successful, it is crucial that the mechanical performance and durability of cement-based materials are not significantly reduced. In this connection, strengthening low-strength and degraded cement-based systems can play a critical role. If efficient strengthening techniques are available, concrete elements may be produced using lower cement content (the reduction of properties can be compensated via the effective strengthening). Concerning the reuse of structural concrete elements, the mechanical and durability properties of recycled components may deteriorate significantly over their service life. Consequently, strengthening treatments are probably required to restore or enhance their performance, ensuring compliance with safety standards and regulatory requirements.

In this work, two strengthening methods were investigated. The first one, denoted as carbonation treatment, aimed to facilitate the formation of calcium carbonate ($CaCO_3$) inside the pores of cement-based materials, thereby improving strength and reducing permeability. It was hypothesized that external calcium ions (Ca^{2+}) from highly soluble calcium salt solutions could be introduced into the pores of cement mortars, and then carbonation reactions could occur by exposing the samples to CO_2 curing, leading to the precipitation of calcium carbonate in the pores. The second approach, referred to as phosphate treatment, was designed to facilitate the in-situ formation of hydroxyapatite (HAP) within cement-based materials. The hypothesis was that calcium-containing minerals in cement hydration products could react with phosphate solutions to form HAP. Since HAP possesses superior mechanical properties than that of hardened cement, the formation of HAP would be beneficial for the overall properties of the materials.

For the carbonation treatment, several calcium solutions ($Ca(NO_3)_2$, $Ca(OH)_2$, and $CaCl_2$) were used and cement mortars with different base compressive strengths (~3-4 MPa, 30MPa, 40 MPa, and 80 MPa) were tested. The results showed that the carbonation treatment could increase the strength of the mortars and

reduce the gas permeability, though the ratios varied depending on the base mortars. A general trend observed was that the strengthening effect reduced with the increase of the mortar strength. It could be attributed to that the mortars with higher strengths tend to have dense microstructure which hinders the penetration of both calcium bearing solutions and gaseous CO_2 into the material bulk, leading to limited formation of $CaCO_3$. One challenge identified was the difficulty in introducing more calcium ions into the porous materials due to the low solubility at high pH when $CaCO_3$ can be formed. The current work demonstrated that the use of high soluble $CaCl_2$ solution together with ammonia promoted the carbonation reactions to some extent.

For the phosphate treatment, diammonium hydrogen phosphate (DAP) was used as the phosphate solution and mortars with rather low compressive strengths (~10 MPa, and 20MPa) were studied. The treatment led to the enhancement of compressive strength (up to 47%), reduction of water absorption (up to 28%), and increase of the ultrasonic pulse velocity values (up to 13%). Despite the relatively good improvement of the properties, it was noted that only a limited quantity of HAP was able to form, primarily located close to the sample surfaces. Formation of the HAP dense layer on the surfaces hindered the penetration of the DAP solution further into the samples, being a significant constraint limiting the effects of the treatment.

Overall, both the carbonation and the phosphate treatments showed moderate effects in improving the properties of (rather low strength) cement mortars. Meanwhile, certain challenges and limitations remain. If the constraints can be properly addressed, significantly improved outcomes may be achieved, presenting promising directions for future research.

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Advances in Rubberized Cement Composites a Comprehensive Review of Properties and Applications

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Keywords: End-of-life tyres (ELT), Rubberised cement composites (RCCs), Crumb rubber recycling, Sustainable construction materials, Environmental resilience in concrete.

Abstract: End-of-life tyre (ELT) disposal is a difficult global environmental problem which creates excess landfill wastes, environmental pollution, and natural resource consumption. Traditional disposal methods of landfilling and incineration have significant drawbacks of soil and groundwater contamination and release of hazardous substances. These environmental problems have cultivated an increasing interest in recycling and reuse methods that are more sustainable. Among various options explored, the incorporation of crumb rubber from waste tyres into cementitious materials has demonstrated high prospects for sustainable construction. This paper provides a critical review of rubberised cement composites (RCCs) in physical, mechanical, and environmental performance by utilising crumb rubber as a partial replacement of traditional aggregates in concrete. The method involves a critical examination of the literature of experimental studies assessing the key properties, including acoustic attributes, mechanical behaviour, air entrainment, and freeze-thaw resistance in saltwater and freshwater environments. Furthermore, comparative findings from various studies are considered to contrast the merits and limitations of RCCs for various applications. The results indicate that the addition of crumb rubber significantly enhances thermal insulation and sound absorption, and thus, RCCs can be an effective and sustainable solution for modern construction, particularly in resource-scarce regions. The elastic behaviour of the rubber particles assists in enhancing impact resistance and flexibility and thus renders RCCs suitable for application in infrastructure requiring toughness under dynamic loading, e.g., roads, bridge decks, and earthquake-resistant structures. However, excessive loss in compressive strength and workability inconsistencies remain overriding concerns. These detriments can be mitigated through the application of optimised mix designs, surface treatment of rubber particles, and incorporation of supplementary cementitious materials (SCMs) such as silica fume and fly ash for improving strength and enhancing durability. The study further highlights RCCs' potential to assist in improving building and infrastructure acoustic performance. Due to the inherent porosity and elasticity of rubber, RCCs are good at disrupting sound wave propagation, leading to improved noise reduction. Research demonstrates that RCCs can minimise airborne sound levels by up to 30% and are predestined for noise-sensitive uses such as residential and school buildings, hospitals, and highway noise barriers. From the environmental perspective, RCCs enable the circular economy by recycling waste tyres, reducing the need for non-renewable natural aggregates, and lowering the ecological footprint of concrete production. The better freeze-thaw resistance and impact durability of RCCs also support their application in large-volume infrastructures. Long-term durability studies are, however, needed to establish their ageing behaviour under varying environmental exposures, including moisture, chemical attack, and temperature fluctuations. Furthermore, nanomaterials like graphene oxide and nano-silica are being explored for enhancing cement matrix densification, reducing permeability, and achieving enhanced mechanical performance. Digital modelling and artificial intelligence-driven mix optimisation protocols should assist in accelerating large-scale RCC adoption through the potential of more precise formulation with optimised strength, durability, and sustainability. By encouraging more extensive application across the global construction industry, this review demonstrates RCCs' prospects for developing sustainable, affordable building materials. Applications in low-income housing, pavement of roads, and climate-resistant structures demonstrate how they can potentially transform conventional building practices. As research

continues to evolve, RCCs will almost certainly be expected to contribute substantively to environmental sustainability, resource sustainability, and socio-economic development. Through the integration of novel materials and construction methods, rubberised cement composites offer a viable route toward more sustainable construction in alignment with international sustainability targets.

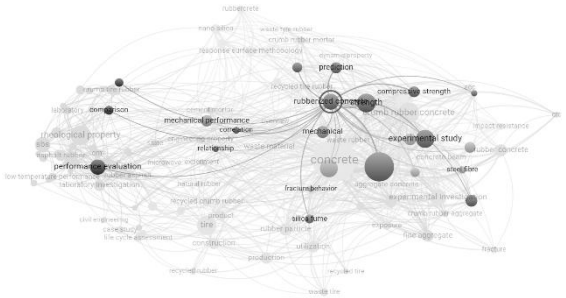

Figure 1. Publication search results network mapping from the Scopus database using the keyword "rubberized concrete".

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An innovative biological technique utilizing microalgae to improve the stability of gypsum

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Keywords: microalgae, gypsum, biochar, retardation

With the global construction sector rapidly advancing toward carbon neutrality, the development of low-carbon building materials has become a critical priority. Gypsum, a widely utilized traditional construction material, requires retarders to modulate its rapid setting characteristics. However, conventional chemical retarders (e.g., citric acid, protein derivatives) rely on energy-intensive production processes, emitting 2–5 tons of CO_2 per ton of product, alongside toxic byproducts such as organic wastewater and volatile solvents, posing persistent ecological risks. Although natural polysaccharide-based retarders (e.g., cellulose, chitosan) exhibit potential in delaying hydration rates, their industrial adoption remains constrained by energy-demanding purification processes. For instance, chitosan production involves deacetylation of chitin extracted from crustacean shells, consuming 15–20 MJ/kg and achieving only a 30% reduction in carbon emissions compared to synthetic counterparts—insufficient to meet net-zero objectives.

To address these challenges, this study proposes microalgae-derived materials as innovative retarders. Spirulina, a cyanobacterium with exceptional carbon sequestration capacity (1.8 tons of CO_2 absorbed per ton of dry biomass), requires minimal processing—simple drying and mechanical grinding—reducing energy consumption by over 70% compared to traditional methods. Experiments were conducted by incorporating 1%–5% Spirulina powder and its pyrolyzed biochar (produced at 300°C under nitrogen atmosphere) into desulfurized gypsum to systematically evaluated their effects on setting time, mechanical properties, and carbon footprint. The results revealed significant performance disparities between unmodified algae powder and biochar. Native Spirulina powder, enriched with hydroxyl (-OH) and carboxyl (-COOH) functional groups, demonstrated exceptional retardation efficacy. At a 5% dosage, the initial setting time of gypsum was extended by 203%, far exceeding the 120% efficiency of conventional retarders. In contrast, biochar completely lost its retarding capacity due to thermal decomposition of functional groups during pyrolysis. Low dosages of algae powder (1%–2%) slightly reduced compressive strength (8%–15%) while markedly enhanced slurry yield stress (40%–60%), improving workability and anti-settling performance. Life cycle assessment (LCA) highlighted the environmental superiority of algae-based formulations: the incorporation of 5% Spirulina powder achieved net-negative carbon emissions (-0.23 $kgCO_2e/kg$), attributed to its "carbon-negative" production chain. Traditional retarders exhibited emissions of 1.2–3.5 $kgCO_2e/kg$, whereas algae powder reduced the carbon footprint by 31%–86% across all tested dosages.

This study overcomes the technical limitations of direct biomass utilization in construction material functionalization, enabling transformative applications:

1. Low-Carbon Gypsum Board Production: Substituting >30% of traditional retarders with cost-effective algae powder (< $0.5/kg) to manufacture carbon-neutral gypsum boards, enhancing cost efficiency in prefabricated construction.
2. 3D-Printable Composite Development: High-thixotropy algae-gypsum composites address interlayer defects in 3D-printed structures by optimizing flowability and structural cohesion, enabling complex architectural geometries.
3. Closed-Loop Carbon Capture Systems: Direct utilization of CO_2 from industrial flue gases (e.g., steel plants, power stations) for large-scale algae cultivation establishes an integrated "carbon capture-retarder production-construction application" chain, capable of sequestering over 10,000 tons of CO_2 annually and transitioning the industry from a carbon source to a carbon sink.

This research provides an innovative pathway for high-value biomass utilization and construction decarbonization, marking a technological leap from emission reduction to carbon negativity in green building materials.

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An Innovative Structural Energy Storage Solution using Fly Ash-Cement Composites for Net-zero Energy Buildings

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Keywords: Cement; Fly ash; Zinc-ion hybrid supercapacitor; Pore structure; Scalable energy storage

Introduction
The construction industry, responsible for nearly 40% of global carbon emissions, urgently requires sustainable solution to achieve net-zero energy buildings (NZEBs). Structural supercapacitors (SSCs) that integrate renewable energy storage directly into structural components have emerged as promising candidates. However, conventional SSCs face challenges in balancing mechanical strength, ionic conductivity, and scalability. Traditional additives such as alkali metal salts or organic polymers often compromise durability and safety. In addition, existing pseudo-capacitor metal oxides suffer from low energy density and complex fabrication. Aqueous zinc-ion hybrid supercapacitors (ZHSCs) have emerged as a promising energy storage technology, offering eco-friendly and exceptional electrochemical performance. In this study, a novel structural energy storage device is designed by integrating ZHSCs with porous fly ash (FA)-cement composites. The microstructure of porous FA-cement composites and the energy storage performance were investigated. Simultaneously, the carbon emissions and energy saving rate of SSCs were evaluated. This approach aims to enable large-scale building-integrated energy storage, and provide a high-value application of industrial solid waste.
Methodology
The composites were prepared using a water-to-binder ratio of 0.5, incorporating aluminium powder as a foaming agent. The samples (CON group and FCS group) underwent curing for varying durations and immersed in 2M $ZnSO_4$ solution. The active carbon cathode, composites and zinc anode were assembled to fabricate SSCs. The compressive strength and ionic conductivity were measured. The microstructure was characterized via XRD, TG, SEM-EDX, MIP, and X-CT. Electrochemical performance was evaluated through CV, EIS, and GCD. The capacitance, energy density, powder density and long-cycling stability were measured, alongside assessments of CO_2 emissions and energy saving rates.
Results
The optimized FCS with 50% FA achieves a peak ionic conductivity of 25.6 mS cm^{-1} and compressive strength of 5.5 MPa after one day of curing. The compressive strength of samples soaked in $ZnSO_4$ solution exhibit significantly higher compared to those soaked in deionized water. XRD and TG analysis confirm the additional formation of gypsum and zinc sulfate hydroxide hydrate (ZSH) in samples soaked in $ZnSO_4$ solution. SEM images reveal a uniform and dense morphology of FCS with a significant abundance of finely distributed ZSH and gypsum on the matrix surface. Moreover, the addition of FA contributes to the connectivity of pore structure with uniformly distributed pore sizes. MIP data highlights the pore exceeding 200 nm decreases and pores smaller than 20 nm increases after adding FA, enhancing both ionic pathways and mechanical property. The FCS-SSCs demonstrate a specific capacitance of 102.4 mAh g^{-1} at 0.1 A g^{-1}, an energy density of 73 Wh kg^{-1}, and a power density of 76.3 W kg^{-1}, with 92.9% capacitance retention over 2000 cycles. Bulk SSCs of 100 cm^2 can power LED for hours, validated scalability for building-integrated applications.
Discussion
FA influences the ionic transport within FCS through multiple mechanisms. During the foam formation process, FA particles with spherical geometries function as ball bearings, facilitating the homogeneous dispersion of bubbles. In addition, FCS generates sparsely distributed hydration products, while gypsum and ZSH grow within the pore structure, further refining it and strengthening the overall matrix. Protons are absorbed near the surface of the zinc electrode accompanied by the Faradaic reaction, while adsorption-desorption occurs at the active carbon cathode. The cycling stability stemmed from the homogeneous pore

architecture, which suppressed zinc dendrite formation and ensured uniform charge distribution. The significant reduction in CO_2 emissions can be attributed to the abundant availability of electrode materials and the incorporation of FA. In addition, the device serves can releases electricity, further facilitating carbon reduction. With the energy density achieved in this study (i.e., 0.37 kWh m^{-3}), the required replacement ratio of SSCs to completely offset the electricity consumption is 42.3% in China and 46.6% in the United States.

Conclusion

In this study, a novel ZHSCs featuring a porous FA-cement composites containing 50 wt.% FA was developed. The incorporation of $ZnSO_4$ electrolyte enhances both the ionic conductivity and mechanical property. The addition of FA significantly improves the energy storage performance of SSCs by creating a uniformly distributed and refined pore structure. The resulting energy storage device demonstrates a superior specific capacitance of 102.4 mAh g^{-1}, high energy density of 73 Wh kg^{-1}, and remarkable cycling stability. These superior performance metrics, coupled with the structural utility and widespread availability of cement and FA, highlight the potential of SSCs in achieving net-zero energy consumption in buildings and enabling self-charging systems in extreme environment. Additionally, this study offers a novel strategy for the high-value application of substantial solid wastes.

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Aqueous carbonation and enhancement mechanisms of solution chemistry of amorphous calcium (alumino) silicates based solid wastes

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Keywords: Aqueous carbonation; Amorphous calcium aluminosilicates; Solution chemistry; Carbonation kinetics, Surface chemistry.

Amorphous calcium (alumino)silicates present in various industrial solid wastes are key determinants of their reactivity. Current research has established that the pozzolanic and alkali-activated reactivity of these materials strongly depends on the atomic-scale structure of the amorphous phase, particularly the connectivity of [SiO_4] tetrahedra through Si–O–Si bonds forming disordered network structures, and dissolution kinetics are enhanced by higher degrees of network depolymerization, which correlates with increasing concentrations of network-modifying cations (e.g., Ca^{2+}, Na^{+}) in the glassy phase. Despite these advances in understanding alkaline activation mechanisms, the carbonation behavior of amorphous phases under acidic conditions (induced by CO_2 injection) remains poorly characterized. This knowledge gap is particularly critical given the growing importance of solid waste carbonation technologies, where the reactivity of amorphous components may fundamentally control the overall carbonation efficiency of industrial byproducts. To enhance carbonation efficiency, this study systematically investigates the aqueous carbonation behavior and solution chemistry-mediated enhancement mechanisms of phosphorus slag (PS) and blast furnace slag (SG). The carbonation processes of PS and SG were monitored in real time through pH measurements, conductivity tracking, and quantitative analysis of ionic concentration evolution. To characterize the phase transformations, a multi-technique approach was employed, including Fourier-transform infrared spectroscopy (FTIR), solid-state nuclear magnetic resonance (NMR), thermogravimetric analysis (TGA), and X-ray diffraction (XRD). Furthermore, the surface chemical composition and morphological changes of the carbonated products were analyzed using X-ray photoelectron spectroscopy (XPS) and scanning electron microscopy (SEM), respectively. Structural characterization revealed that both solid wastes contained over 90% amorphous content and different aluminosilicate polymerization, with SG exhibiting a lower degree of [SiO_4] tetrahedral connectivity (96.87% Q^0 species) compared to PS (81.09% Q^0), meanwhile, more tetrahedrally coordinated aluminum in SG suggests its role as a network former in the aluminosilicate framework, potentially influencing calcium ion dissolution behavior through structural modifications of the silicate network. Comparative analysis of the pure H_2O-CO_2 system and the $NaHCO_3$ system revealed significant differences in the dissolution-carbonation kinetics of PS and SG, accompanied by distinct transformations in the saturation states of product phases. Notably, both silica gel and calcite reached supersaturation in the PS system, whereas they remained undersaturated in the SG system. In contrast, the introduction of $NaHCO_3$ led to three key behavioral divergences: (i) a nearly two-order-of-magnitude reduction in calcium concentrations compared to the pure system; (ii) a shift in phase saturation states-for PS, calcite remained supersaturated while silica gel transitioned to undersaturation, whereas for SG, calcite approached supersaturation and silica gel persisted in an undersaturated state as $NaHCO_3$ concentration increased; and (iii) minimal sensitivity of the system to variations in carbonation time and temperature. Notably, in the $NaHCO_3$ system, the total calcium carbonate (Cc) content in PS increased by more than an order of magnitude within 30 min, whereas SG exhibited only a marginal increase (~1×) even

after 6 h. These disparities primarily stem from structural alterations induced by aluminum within the amorphous silicate network, particularly the formation of an aluminum-silica gel layer on SG particle surfaces. This layer arises from the incorporation of aluminum into the silica framework via Al–O–Si bonding, which significantly retards ion dissolution and carbonation kinetics. The Al/Si atomic ratio of an aluminum-enriched silica gel outer layer for SG progressively increased from 0.55 to approximately 0.75 with rising $NaHCO_3$ concentration, accompanied by the rapid aluminum incorporation kinetics. In contrast, PS exhibited a divergent trend, highlighting distinct carbonation behaviors between the two materials. Notably, the Ca/Si ratios of PS and SG exhibited opposing evolutionary trends during carbonation. In PS, the Ca/Si ratio increased sharply from approximately 0.75 to 1.8 upon $NaHCO_3$ addition, suggesting substantial calcium carbonate deposition on the particle surfaces, however, SG displayed only minor fluctuations in Ca/Si ratio with values remaining significantly lower than those of PS, which indicate limited carbonation progression and minimal calcium carbonate adhesion on SG particles. The enhancing effect of $NaHCO_3$ is attributed to the elevated carbonate ion concentration under higher pH conditions, which facilitates calcium ion complexation and accelerates carbonation. However, the reaction kinetics for both slags in the $NaHCO_3$ system were predominantly confined at the early stages due to the rapid formation of a passivating surface layer—comprising primarily calcite deposits for PS and aluminum-silica gel adsorption for SG. This dense layer impeded subsequent ion diffusion and dissolution, thereby suppressing prolonged carbonation progression.

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Assessing CO_2 uptake by cementitious materials for life cycle analysis: flux measurement and thermogravimetric analysis

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Keywords: Precast concrete, carbonation, CO_2 flux measurement, LCA, EPD, durability, environmental impact.

Current Life Cycle Assessments (LCAs) and Environmental Product Declarations (EPDs) for concrete often rely on standards rather than real-time monitoring to account for CO_2 uptake due to carbonation. This can lead to inaccuracies in assessing the real environmental impact of concrete. In response, this paper presents a non-destructive, instantaneous CO_2 flux measurement protocol designed to monitor the amount of bound CO_2 in cementitious materials.

The proposed method captures the carbonation process in concrete by measuring the flux of CO_2 at the surface in the carbonated zone. Validation of the protocol is achieved by applying it to ready mix and precast concrete and comparing its results with those obtained from thermogravimetric analysis (TGA) and the European standard EN 16757. The European standard EN 16757 provides guidance on calculating CO_2 uptake by carbonation based on the depth of carbonation, binder composition and exposure conditions. TGA is used to evaluate the carbonation rate of the different layers of the studied concrete to reconstruct the carbonation profile and assess its rate. The non-destructive method measures the CO_2 flux in the carbonated zone of the concrete. The CO_2 flux dCO_2/dt is then integrated into bound CO_2. The study further explores the application of the protocol for monitoring carbonation in existing structures and predicting the long-term behavior of ready mix and precast concrete specimens, specifically during post-fabrication, storage, installation on-site and the use phase.

The study covers two cases ready mix and precast concrete. For ready-mix concrete, carbonation during on-site installation and the use phase is measured. For precast concrete, early-stage flux data collected during both post-fabrication and storage stages are collected. A validation study was conducted on calcined clay concrete in both controlled laboratory settings and sheltered exposure to reflect storage (65% RH chamber) and on-site installation (sheltered) exposure conditions. The results indicate that the suggested method enables the assessment of carbonation and effectively captures the influence of factors such as porosity and material composition on CO_2 uptake. It enables a real-time evaluation of variations in carbonation rate evolution.

The non-destructive CO_2 flux measurement protocol presented in this study demonstrates good accuracy compared to thermogravimetric analysis (TGA) and the European standard EN 16757 in evaluating bound CO_2. Applicable to naturally carbonated concretes under realistic exposure conditions, it provides a practical and reliable method for directly monitoring CO_2 uptake in carbonatable materials. This approach enhances the precision of carbonation accounting in Life Cycle Assessments (LCAs) and Environmental Product Declarations (EPDs), particularly for low-carbon and modern concretes, where traditional carbonation laws (such as the square root of time law) do not apply and where carbonation depth and bound CO_2 are not always correlated. Future work will focus on developing predictive carbonation models and integrating the protocol into standardized industry practices to enhance carbonation assessment in concrete production.

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Assessing the CO2 saving potential of Phase Change Materials in Buildings: Effect of Melting Temperature, Thickness, and Placement on Energy Demand

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Keywords: Low-CO2 building design, Phase Change Materials, CO2 saving, Sustainable Buildings.

The construction industry is facing an increasing pressure to reduce operational CO2 emissions, especially in residential buildings which often have high energy demand for space conditioning. Phase change materials (PCMs) offer a promising solution through storing and release of thermal energy during phase transitions, which reduces energy consumption and associated CO2 emission. This study assesses the CO2 savings potential of PCMs in a single unit terrace building by evaluating the effects of three design parameters which are, melting temperature, PCM thickness, and placement, on energy demand profiles.

A Taguchi L9 orthogonal array was used to systematically analyse the effects of the design parameters, which allowed us to study efficiently the combined effect of these factors with minimal simulation runs. The three factors were considered at three levels: melting temperature (18 degrees Celsius (°C), 21°C, 23°C), PCM thickness (0.02 meters (m), 0.04m, 0.06m), and placement (wall, roof, floor). This resulted in 9 simulation runs, each representing a unique combination of these factors. For example, Run 1 used a melting temperature of 18°C, a thickness of 0.06m, and wall placement, while Run 2 used 18°C, 0.04m, and roof placement. The simulations were conducted using DesignBuilder software which runs on energyplus using climatic data of Eindhoven Airport. The building model included standard construction materials, with PCM layers integrated into the specified placements (wall, roof, or floor).
Energy demand profiles, consisting of heating and cooling loads in kilowatt-hours (kWh), were calculated for each run over an annual cycle. Interaction plots were generated to visualize the effects of each factor and their interactions on energy demand. CO2 savings were then estimated using an emission factor of 0.5 kilograms of CO2 per kilowatt-hour (kg CO2/kWh).

Early results from this study provide initial insights into the effects of the design parameters. Simulation run-9 (23°C, 0.02 m, roof) exhibited the highest mean heating energy demand, likely because the melting temperature exceeded the ambient temperature, preventing phase changes. In contrast, run-3 (18°C, 0.02 m, floor) showed the lowest mean heating demand, suggesting that a lower melting temperature in the floor, with minimal interaction with the outdoor environment, enhances heating efficiency. For cooling, run-6 (21°C, 0.02 m, wall) had the highest mean cooling energy demand, while run-1 (18°C, 0.06 m, wall) had the lowest, indicating that a thicker PCM layer at a lower melting temperature in the wall allows the PCM to solidify during cooler periods, reducing cooling needs. Mean operative temperatures remained stable across all runs due to a heating setpoint temperature of 18°C, suggesting PCMs buffer temperature extremes without significantly altering average indoor conditions. At the conference, we will present comprehensive results, including CO2 savings across configurations and detailed interaction analyses.
In conclusion, early results suggest PCMs in buildings can reduce its energy demand which is a reflection of the CO2 footprint of the building. The Taguchi L9 approach and interaction plots provide a robust

framework for understanding factor effects, offering insights for low-CO2 building design. Future work will include optimization and lifecycle assessments.

Assessment of the Potential of In-Line Spectroscopy Techniques combined with CNN model for Classifying the Fine Fraction in CDW

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Abbreviations:

CDW, Construction and Demolition Wastes; **NIR**, Near Infrared; **LIBS**, Laser Induced Breakdown Spectroscopy; **UV**, UV-Visible; **CNN**, Convolutional Neural Networks.

Keywords: CDW, spectroscopy, deep learning, CNN, circularity

Abstract:

In the construction sector, an outstanding issue is the management of Construction and Demolition Wastes (CDW) due to the large quantity generated and their significant environmental impact. Effective recycling or upcycling of these materials requires proper characterization and sorting of their components. In this context, advanced techniques such as spectroscopy and image processing, combined with machine and deep learning models, offer promising solutions for identifying and classifying different components. CDW can be divided into two distinct groups based on particle size: coarse fraction (>4mm) and fine fraction (<4mm). For coarse fraction, considerable research has demonstrated the applicability of hyperspectral cameras or LIBS for classification and sorting.

Despite recent advancements aimed at ensuring high-quality recycled materials, fine fractions, and ultrafine fractions (<1 mm) from CDW still face significant technical barriers to being incorporated into new materials and products. The difficulty in identification and sorting these materials due to their small size and heterogeneity often leads to their frequent disposal in landfills. Although recent research has begun exploring the application of individual spectroscopic techniques, such as Raman, SWIR, and LIBS, for the detection of unwanted materials, this field remains in its early stages, presenting substantial potential for future research and breakthroughs.

This study assesses the potential of four in-line spectroscopy techniques Near-Infrared (NIR), Laser Induced Breakdown Spectroscopy (LIBS), Raman and UV-Visible (UV) combined with deep learning algorithms for identifying and classifying the most common components in the fine fraction of CDW. Eleven controlled materials are analysed using conventional laboratory techniques. The materials were cement paste, polyethylene, iron, limestone, siliceous aggregate, ceramic fraction, recycled limestone concrete aggregate, siliceous mortar, gypsum, wood, and glass powder.

To generate the dataset, a multi-sensor device equipped with the four techniques mentioned above, is used to acquire spectroscopy data from the materials. For each technique, 1024 spectra are obtained for each material, yielding a dataset of 11264 spectra. The data are pre-processed, according to the technique concerned, and then a PCA is applied for the interpretation of the data. Finally, four classification models have been trained, each for a specific type of sensor data. The models are based on a deep learning architecture that employs one-dimensional convolutional layers (1D CNNs) to process the spectral data. This approach enables the execution of multiclass classification tasks, allowing for effective feature extraction and classification across different sensor modalities. Performance is evaluated using confusion matrices and metrics in each subset.

Regarding the test set, the results achieved for each technique, in terms of recall, precision, and F1 score, are as follows: LIBS (92.5, 93.8, 92.4)%, NIR (67.2, 66.6, 62.7)%, Raman (98, 98, 98)% and UV-Vis (89.9, 90, 89.2)%. The results demonstrate that the training models exhibit high potential for accurately classifying the studied materials. All sensors can differentiate between organic and inorganic. Notably, LIBS and Raman outperform NIR and UV in distinguishing inorganic materials, particularly aggregates.

This study has significant implications, as accurate classification and characterization of the fine fraction of CDW can enable the reuse and recycling of valuable materials, thereby reducing landfill waste and mitigating environmental impact. Moreover, the implementation of in-line spectroscopic techniques in the construction industry can improve efficiency and productivity in waste classification and characterization.

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Can wind turbine blade waste be used as a cementitious material?

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Keywords: Wind turbine blade waste, Supplementary cementitious materials (SCMs), Pozzolanic activity, Leaching

Abstract - The disposal of decommissioned wind turbine blades (WTBs) poses a growing environmental challenge. This study investigates the potential of using waste WTB materials as supplementary cementitious materials (SCMs) in concrete. Three different WTB wastes were characterized using X-ray fluorescence (XRF), X-ray diffraction (XRD), R3 calorimetry, and leaching tests. The results show that WTB wastes exhibit pozzolanic activity and release limited amounts of potentially harmful elements, suggesting their suitability as SCMs. This approach offers a sustainable solution for WTB waste management and contributes to the development of more environmentally friendly concrete.

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Changing the culture, in concrete

Boudewijn Piscaer, Pantheon Performance Foundation

Keywords: Culture, Mineral Composite, Standardizations, Real-Crete, Education.

Abstract:

Not the lack of knowledge, but the culture of the industry and its place in society are obstacles for innovation implementation. The huge environmental impact of concrete and resource efficiency are the motivations. For the basically High-Tech Mineral Composite called concrete to obtain a true vital role for mankind, the culture of the construction economy and in particular concrete must evolve. Doing more with less, moving from volume and mass to high quality and insuring proper financial contributions for all parties in the value chain. Several fundamental anomalies are highlighted and exposed in standardizations, lack of education on all levels and proper verification on performance instead of prescriptive standards imposed by dominant market forces. Confusion in basic terminology is exposed. Differences between so-called LabCrete and RealCrete highlight a global problem that exposes the fact that we do not have reliable data of what has been constructed. Suggestions are made on how to improve the concrete economy and reference to an upcoming proposal for Education on ALL levels, especially non scientific, is made.

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Characterisation of Recycled Concrete Aggregates with TGA and XRF coupled with Statistical Data Analysis

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Keywords: CO_2 sequestration, Recycled Concrete Aggregates, statistical data analysis, hydrothermal carbonation.

The construction sector faces several challenges today, such as high CO_2 emissions and the increasing generation of mineral waste. To address these challenges, it is essential to develop new recycling strategies and technologies for cementitious building materials.

One approach to recycling concrete waste is the accelerated carbonation of Recycled Concrete Aggregates (RCA). Carbonating the RCA leads to the sequestration of CO_2 in the cement matrix of the material. Furthermore, carbonation improves the physical properties (e.g. decreasing porosity) of the RCA. Consequently, carbonated RCA are well-suited for replacing natural aggregates in fresh concrete.

To date, there is no established accelerated carbonation process for RCA as there are several challenges to overcome when developing and optimising the carbonation process. The goal is to achieve a complete carbonation of the material in a short time. The carbonation is often assessed quantitatively based on a CO_2-uptake or a carbonation degree.
Thermogravimetric analysis (TGA) is commonly used to determine the amount of CO_2 stored in a sample during carbonation. For this, the sample must be analysed before and after the carbonation treatment. However, this method is not directly applicable to real RCA samples as the samples need to be ground and the RCA vary in terms of their cement content, aggregate quantity and aggregate type.

The aim of the study was to find a methodology for the characterisation of Recycled Concrete Aggregates from old paving stones. Moreover, it is assessed whether this type of characterisation is valid for investigating the CO_2-uptake during the carbonation under different conditions.

In a first step, a theoretical carbonation potential was calculated. This is based on the CaO-content of a sample. The calculation of the maximum CO_2-uptake of a sample is predicated on the assumption that all non-sulphate-bound CaO is converted into $CaCO_3$ and that no other phases react with CO_2.

In a second step, 14 cylindrical samples (2,5 cm diameter, 1 cm height) from the not carbonated cores of old paving stones were analysed by TGA to determine the amount of bound CO_2 before an accelerated carbonation. The measured CO_2 can originate from $CaCO_3$ aggregates or small quantities of already carbonated cement paste. Furthermore, each sample was analysed by X-ray fluorescence analysis (XRF) to determine the CaO-content. The CO_2- and CaO-contents of the samples are plotted in Figure 1.

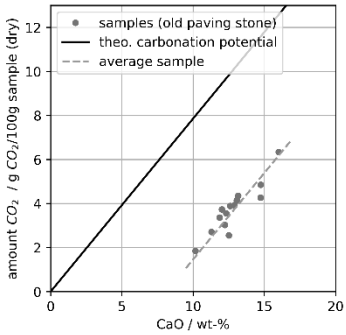

Figure 11: CO_2- and CaO-contents of samples from old paving stones (green dots). The theoretical carbonation potential is shown as a black line.

It shows that the CaO-contents of the samples are in a certain range. Deviations in CO_2-content are observed at the same CaO-content. Therefore, averaged CO_2/CaO-values (average sample) were used for further analysis. The deviations between the averaged CO_2/CaO-values and the experimental data were calculated in the study.

In a third step, accelerated carbonation experiments with cylindrical samples from the same old paving stones were carried out under three completely different conditions:

Hydrothermal carbonation: p_{CO_2} = 4 bar, T = 170 °C, t = 4 h
Air carbonation: p = 1,013 bar, T = 20 °C, t = 4 weeks
Moderate carbonation: p = 1,013 bar, T = 20 °C, t = 4 weeks, c_{CO_2} = 40%, rH = 40%

After the carbonation experiments, the samples were analysed by TGA and XRF. To determine the CO_2-uptake due to the carbonation, the averaged CO_2/CaO-values (average sample) from the second step were used as a reference basis. For the calculation of a carbonation degree, the theoretical carbonation potential from the first step was considered.

As a result, a CO_2-uptake was observed in all carbonation experiments. Moreover, the study discusses the observed CO_2-uptake as a function of the carbonation conditions. However, a significant comparison between the different carbonation experiments was limited, due to the wide spread of data points (amount of CO_2) within the carbonation experiments and the small number of investigated samples.

As a conclusion, the study shows that a characterisation of inhomogeneous RCA is possible with the combination of analytical methods (TGA, XRF) and a subsequent statistical data analysis. Moreover, the methodology can be used for an initial assessment of the CO_2-uptake of RCA. In order to investigate the individual factors influencing the carbonation, additional samples need to be analysed and the statistical impacts on the results have to be considered carefully.

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Characterization Tools for Recycled Concrete Fines for Use as Supplementary Cementitious Materials

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Keywords: Recycled Concrete Fines (RCF), Supplementary Cementitious Materials (SCM), Characterization, Water Demand, Packing Properties

Recycled Concrete Fines (RCF) are the fine fraction obtained from the recycling of concrete construction and demolition waste. RCF is attracting increasing attention as a sustainable feedstock for cement and concrete products. The use of RCF in cement and concrete as supplementary cementitious material (SCM) is generally seen as a promising solution to reach recycled content and decarbonisation targets set forth by governments and companies. As such, RCF has been recently adopted in European standards (EN 197-6:2023) to support their market introduction in multi-constituent cements.
The suitability for use as SCM of RCF mainly depends on its physical properties and chemical/mineralogical composition. In general, RCF contains a significant (20-60%) hardened cement paste, which confers the material with a high specific surface area and irregular surface morphology. In return, RCF water demand and particle packing properties may present challenges for cement workability and compaction. Moreover, the composition and physical properties of RCF varies significantly from source to source and even batch to batch, depending on parent concrete composition as well as recycling and other treatments. Effective screening tools to check or optimize RCF properties appear to be missing. This study, therefore, aims to contribute to better understanding and capturing compositional and physical property variability of RCFs by exploring and proposing novel characterization techniques for RCF, with a focus on water demand, packing properties, and reactivity. The new characterization techniques are combined with complementary chemical/mineralogical analysis and applied to RCF samples originating from various suppliers in Belgium and the Netherlands, covering a range of cementitious materials. For benchmarking, comparisons were made with reference SCMs and fillers, such as ground granulated blast furnace slag (GGBFS), metakaolin, and limestone.

The material characterisation strategy comprised measurement of the chemical and mineralogical composition, as well as physical properties such as particle size distribution analysis, specific surface area, and density. The chemical composition was determined using X-ray fluorescence (XRF) and inductively coupled plasma optical emission spectroscopy (ICP-OES). X-ray diffraction (XRD) was used to identify and quantify crystalline phases and to estimate the amorphous content using internal and external standard approaches. Profex was used to perform Rietveld analysis on the XRD diffractograms in order to quantify the mineral composition of the RCF samples. Fourier-transform infrared spectroscopy (FTIR) provided insights into the presence of silicate network polymerization and hydration products. The thermal behaviour of the samples was studied via thermogravimetric analysis (TGA) to quantify the amount of bound water, portlandite, and carbonate phases. Particle size distribution was determined using laser diffraction, providing insights into the fineness of the RCFs. Surface area and porosity measurements were carried out using Brunauer–Emmett–Teller (BET) analysis. Surface area is a crucial characteristic for

understanding the water demand and reactivity potential of the materials. In addition, it could be considered as an indication of hydrated cement paste content. Scanning electron microscopy (SEM) was conducted to observe the morphology of RCF samples.
Complementary to material characterization, new screening tests were performed more closely related to material performance (e.g. workability, strength development, etc.). Reactivity as an SCM was assessed using the R3 test and compared with other SCMs. Water demand and packing fraction were evaluated to estimate the workability and particle packing behaviour of RCFs in cementitious mixtures. Both water demand and packing property tests were conducted on pastes using a centrifugation method, based on a new method described in the literature. Water demand was determined through measuring the mass of water retained after centrifugation by weighing the centrifugated paste before and after drying at 105 °C. The packing fraction was assessed by determining the difference in the volume of the dry and wet samples before and after centrifugation.

The results demonstrated significant variations in the composition and properties of RCFs, depending on their source. XRF analysis revealed significant differences in CaO and SiO_2 content, indicating different amounts of hydrated cementitious phases and sand/aggregates. XRD analysis confirmed that amorphous content varied among the samples. In addition, it demonstrated that some samples contained high calcite amounts while others contained hydrated phases such as C-S-H and ettringite. The estimated paste content based on XRF-XRD comparison provided additional information regarding the amount of hydrated phases present in the amorphous fraction.
Water demand tests indicated that some RCFs required a water amount comparable to GGBFS. This result is promising in terms of the potential use of these RCFs as SCM, as it indicates that they could be used in similar proportions to regular SCMs without a significant change in water absorption or workability. Packing fraction measurements indicated that variations in particle size distribution and shape influence particle packing efficiency in blended cements. It is generally accepted that fine particles fill the voids between coarser ones, enhancing compactness and reducing porosity. Additionally, irregular or angular particles create more voids, decreasing packing efficiency, whereas spherical particles improve densification.

A comprehensive characterization study of RCFs from several sources was done to assess the potential of these materials to be used as SCM. The findings of this study suggest the need for beneficiation processes to enhance the performance of RCFs in cementitious reactions. These beneficiation (activation) methods would yield improved physical properties and reactivity of RCFs. Future research will focus on the development of a beneficiation method, particularly a mechanochemical activation approach, to enhance the potential of RCFs for sustainable cement formulations.

Circular Economy Pedagogy Workflow– Reusing Waste Shoes and Waste Tyres in Sustainable Construction Products

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Circular economy (CE) seeks to eliminate waste by innovative systems thinking towards creating closed loop systems. In a CE, all types of waste are minimized to as close to zero as possible. Although the CE strategy has gained popularity, it has fallen short on action; global circularity has decreased from 9.1% in 2018 to 7.2% in 2023, a 21% drop over the course of five years. This study proposed a novel Circular Economy Product Design (CEPD) workflow for CE pedagogy. Students of a pilot CE course transformed shoe and tyre waste into construction materials. The novel CEPD methodology was validated by two proof of concept case studies for pavements and garden fences. Globally, about 24 billion shoes are produced annually and the amount of shoes thrown away annually in the United States of America (USA) is estimated to be around 300 million pairs. These shoes take up a lot of space in landfills and their decomposition produces methane, a greenhouse gas emission that contributes to climate change. The decomposition of shoes and tyres can contaminate local water supplies and agricultural land posing health risks to human and wildlife. The topic of CE was introduced and taught with materials from the USA's Environmental Protection Agency, the European Union and the Ellen MacArthur Foundation. Students' identified wastes from industries for possible symbioses with the construction industry. Thereafter they chose the products for circularity that they would transform existing waste into. In the first circular project, waste shoes were combined with mycelium to produce pavements. In the second design, tyres were combined with recycled plastic and glass for a garden fence. The design stage comprises sketches and building information modelling, design iterations involved two immersive virtual reality sessions. Lastly, environmental and economic impacts were evaluated comparing reuse to recycling, combustion and landfilling. The results showed that applying CE principles to MSW and tyre waste reduces energy consumption and greenhouse gas emissions. This novel method assists colleges in producing graduates equipped with the necessary knowledge and skills of modern tools such as BIM and circular design before they resume their professional careers.

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Combined Activation Strategies for Recycled Concrete Fines as a Mineral Admixture for Portland cement

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Keywords: concrete fines, activation, mineral admixture, Portland cement.

The paper presents experimental results of studying the possibility of using recycled concrete fines (particles with a size less than 1 mm). The fines are the residues of sieving the recycled concrete used as recycled aggregate. Concrete fines serve as a full or partial replacement of blast furnace granulated slag in Portland cement.

As a result of the planned demolition of the buildings due to renovation, as well as unplanned one due to destruction caused by warfare or natural disasters, a significant amount of waste is generated, including concrete, metals, ceramics, polymers, wood, and other materials. A substantial portion of this waste — approximately 60% by weight—consists of concrete debris. After sorting, the concrete waste is typically subjected to mechanical treatment using various types of equipment to produce recycled coarse and fine aggregate. However, during the crushing process, a significant amount (around 10–12%) of fine particles is produced, which are usually not recycled and rather disposed of in landfills, contributing to environmental pollution.

Studies by several researchers have shown that these fine particles consist of a significant amount of potentially reactive particles, including hydrated cement, clinker minerals, and portlandite. These components can serve as supplementary cementitious materials in the manufacturing concrete, mortar, and other construction materials.
As a result of the full-scale war, Ukraine is facing unprecedented levels of destruction, with concrete comprising a significant portion of the resulting demolition waste. Given the scale and urgency of reconstruction efforts, finding effective methods to recycle this material is both a practical necessity and an opportunity to promote circular approaches to recovery.

In Portland cement manufacturing, which is vital for the reconstruction, reducing the clinker content and identifying new sources of effective mineral additives—as alternatives to traditional materials like blast furnace slag, fly ash, and natural pozzolans—is an important strategy for reducing the carbon footprint.
This research was conducted using raw materials typical for Ukraine. Waste of normal-weight concrete aged 8–10 years, containing granite coarse aggregate and quartz sand as a fine aggregate with different cement content, was crushed in the laboratory jaw crusher. Particles smaller than 1 mm were then separated for analysis. These fine particles were characterized in terms of:

- Particle size distribution (via sieve analysis and laser granulometry),
- Chemical and mineralogical composition (via XRD and XRF), and
- Microstructure (using SEM).

The fines had been subjected to additional thermal activation (heating up to 600°C) and the chemical activation. Blended Portland cements have been produced in the laboratory ball mill.
The resulting cements were tested according to standard procedures, including:

- Granulometry,
- Chemical and mineralogical analysis,
- Normal consistency,
- Setting time
- Compressive and flexural strength.

To formalize the data and optimize the parameters for producing Portland cement containing the fines of recycled concrete, a planned experimental design was employed. Polynomial experimental and statistical models were developed for key parameters.

The experiments showed that variations in the composition and strength of the original concrete, as well as the residual content of clinker minerals, had a relatively minor impact on the mechanical properties of the resulting cement at early hardening stage. However, these factors affect grindability, which helped partially compensate the lower reactivity of the fine particles as a mineral additive.

It was found that using unactivated concrete fines can result in lower early strength, failing to meet standard Portland cement strength requirements. However, mechanical activation at grinding, thermal activation (600°C), and the combined use of active mineral additives (e.g., blast furnace slag, metakaolin) and alkali fluoride salts significantly improve performance.

The presence of cement paste and calcium hydroxide in the fines fraction—formed through the hydration of clinker minerals—was shown to influence its reactivity.

The developed mathematical models for water demand, strength, and other properties allowed for analysis of both individual and combined effects of the activation methods and helped identify optimal processing conditions.

The use of combined activation with the inclusion of 15% recycled concrete fines and 15% of blast furnace slag enabled the production of Portland cement of type CEM II/B-M 42,5 N.

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Comprehensive Physicochemical Characterization and Leaching Behaviour of Dutch Wood Biomass Fly Ashes for Sustainable Valorisation

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Keywords: Wood biomass fly ash, Waste Valorisation, Waste recovery

Abstract

Wood biomass fly ash (BFA), a major by-product from bioenergy production, is generated at an estimated global volume of 18.5 million tons annually, with Europe contributing approximately 2.4 million tons. Currently, around 70% of this residue is landfilled, raising significant environmental and economic concerns, particularly in countries with limited land availability such as the Netherlands. To support the sustainable management and potential valorisation of BFA, this study provides a detailed physicochemical characterization of three BFAs sourced from Dutch bioenergy plants. A comprehensive characterization was conducted, including particle size distribution, bulk density, elemental composition, heavy and trace metal concentration, and leaching behaviour. Results showed that all the collected ashes consisted mainly of particles below 100 μm with low contents of pozzolanic oxides (< 30 wt.%) and high leaching risks for Zn, Cr and Pb when compared to the Soil Quality Decree (2022) as non-shaped materials in the Netherlands. The high concentrations for some heavy metals such as Pb, Zn, and Hg, were identified indicating both resource recovery potential and environmental concerns. The comprehensive dataset presented in this study offers a clear overview of the specific challenges that must be addressed prior to successful valorisation of BFA in the Netherlands.

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Compressed (Stabilised) Earth Blocks: Understanding the Impact of Hydraulic Binders in Earth-based Building Materials

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Keywords: Earth Blocks; Regenerative Architecture; Circular Economy; Carbon Neutral; West Africa.

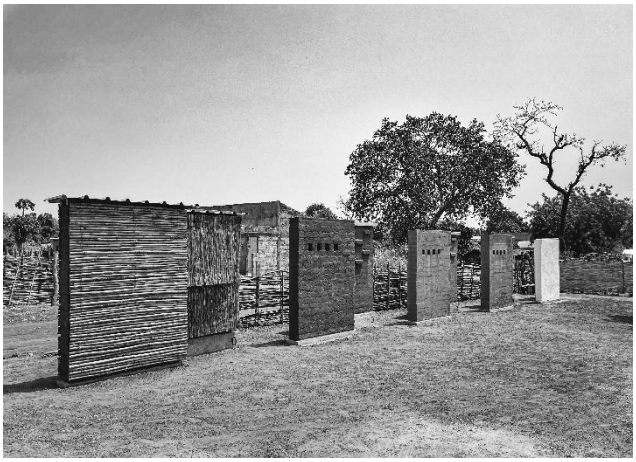
The rapid population growth in West Africa has driven an unparalleled demand for concrete where per capita cement consumption increased even during periods of economic stagnation. With annual consumption projected to triple by 2050 in West Africa and cement's high carbon intensity, emitting approximately 813 kg CO_2 equivalent per ton, this trend poses a significant threat to global climate targets. Despite the presence of a pronounced vernacular architecture, concrete continuous to dominate the West African construction sector, reflecting both its functional versatility and lack of alternatives. However, the dominance of concrete architecture has recently been called into question mostly due to its poor thermal performance in the arid climates of West Africa. Architectural lighthouse projects have employed compressed stabilized earth blocks (CSEBs) as an alternative to hollow concrete blocks and these blocks are increasingly being adapted by local populations. CSEBs are earth-based building blocks that use a hydraulic binder, in most cases cement, and compression to produce a load-bearing masonry unit. The natural binding properties of clayey earth and the strong compression (minimum 30 bars) greatly reduces the amount of cement and sand required when compared to conventional hollow concrete blocks. Additionally, the resulting blocks offer a much greater thermal mass, improving interior room climates. However, the net environmental and cost benefits of CSEBs in the context of building in West Africa have not yet been fully analysed.

This research is based on seven years of working with CSEBs in Senegal and critically reflects their impact on material properties, local ecosystems, and the global atmosphere. Using life cycle assessment (LCA) based on hypothetical designs and built living labs, as well as the monitoring of economic cost of block production, the study relativises the advantages of CSEBs and proposes the implementation of unstabilised compressed earth blocks (CEBs) for use in multistorey buildings.

The study finds that from both an economic and environmental perspectives, CEBs outperform their stabilized counterparts; especially due to their lower primary energy requirements and favourable end-of-life recycling potential. Further, the use of locally available soils and avoidance of processed cement reduces reliance on imported materials and industrial supply chains, to the benefit of local economies. Quantitatively, a reduction of 16 percent in cost and 62 percent in global warming potential (GWP) was found, when comparing housing typologies constructed with CSEBs and CEBs. While improving their economic and environmental properties, avoiding hydraulic binders renders CEBs susceptible to water. Hence, the application of CEBs requires different building elements and components to create resilient structures. The researchers therefore propose optimized soil selection and processing criteria for the manufacturing of high performing CEBs, a model building design for the integration of CEBs according to their inherent properties, and the combination of CEBs with other sustainable materials for a future-proof material palette for urban building in West Africa.

The use of such earth blocks could significantly minimize the environmental cost of construction, with projections suggesting a reduction of up to 1.9 million tons of CO_2 annually if CEBs replace concrete blocks in housing construction across Senegal alone. This article presents research findings featured in the

book *Back to Earth – Urbanization without Depletion* published by Jovis Publishers in 2025. However, this contribution offers an in-depth analysis and new perspectives, with updated data and a focused discussion on the economic and environmental cost of building with C(S)EBs. While the core research is consistent, the article presents a refined methodology and provides new insights that were not included in the book.



Living Lab to investigate Hollow Concrete Block, CSEB and CEB construction in Mako, Senegal.
Image by authors – 2022.

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Development of a Laboratory-Scale Rotating Carbonation Chamber for Recycled Concrete Fines and Its Applicability in Cementitious Systems

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Keywords: recycled-concrete-fines, enforced carbonation, cement,

Global climate change, driven by increasing urbanization and industrial activities, is exacerbated by construction-related resource consumption and greenhouse gas emissions. Cement production, responsible for 8% of global CO_2 emissions, significantly contributes to environmental degradation due to its high energy and raw material demands. Rising cement consumption, driven by construction, demolition, and infrastructure projects, is expected to increase CO_2 emissions further. These activities also generate large amounts of Construction and Demolition Waste (CDW). Recycled concrete from CDW can be processed into aggregates (Recycled Aggregates, RA) and Recycled Concrete Fines (RCF), the latter being particularly valuable due to its high calcium hydroxide ($Ca(OH)_2$) and calcium oxide content. Through mineral carbonation, RCF can act as an efficient carbon sink, capturing CO_2 from cement plant emissions and transforming it into Supplementary Cementitious Materials (SCMs). This process offers environmental and economic benefits by reducing CO_2 emissions and providing a sustainable alternative to clinker in cementitious applications.

This study presents the development of a laboratory-scale, field-applicable dry carbonation unit designed to enhance the CO_2 sequestration of RCF. Revisions have been made on a Los Angeles Abrasion Machine to accommodate a pneumatic hybrid rotary union on the shaft of the non-driving side to stream concentrated CO_2 gas inside the rotating drum. Through a hole drilled on the side of the drum, pressurized, and pre-heated to 60 C°, CO_2 gas is streamed inside the drum. A photoacoustic non-dispersive infrared CO_2 sensor, placed under the carrier shelf inside the drum, controls the CO_2 concentration inside the drum to the desired level with solenoid valves connected to a microcontroller.

To ensure a realistic assessment and accurately evaluate the efficiency of the carbonation unit in mineral carbonation, this study utilizes RCF (<4 mm) sourced from the field instead of laboratory-produced cementitious materials. The efficiency of dry carbonation achieved with the developed equipment was evaluated using the R^3 reactivity test, providing insights into the reactivity and potential pozzolanic behaviour of carbonated RCF. Carbonated RCF was used to replace 10%, 20%, and 30% of cement in cement mortar mixtures prepared at a fixed water-to-binder ratio of 0.40. The influence of RCF on cement mortar performance and hydration of cementitious matrix was comprehensively evaluated through compressive strength tests, flow table, initial setting time measurements, and microstructural analyses, including X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), and Thermogravimetric Analysis (TGA).

The results showed that carbonated RCF possesses pozzolanic activity and increases the particle packing density in the mix. Increasing RCF content led to a significant decrease in workability due to the high specific surface area and water demand of the additives. The incorporation of RCF decreased the initial setting time. The microstructural evaluation revealed that the addition of RCF decreased the amount of calcium hydroxide, indicating pozzolanic activity. At last, using carbonated RCF slightly increased the

compressive strength compared to the control neat samples, up to 20% replacement. Increasing RCF replacement to 30% resulted in a decrease in compressive strength. Nevertheless, the strength measured in the sample with 30% RCF remained within an acceptable range.

The outcomes of this study provide a brief theoretical background on carbon mineralization of a CDW and transform the waste into a raw material for cement manufacturing. The results showed that it is possible to replace 20% of the cement with RCF without sacrificing performance. The study is a key contributor to all components of the chain – clinker, cement, concrete, construction, and concrete carbonation (5C) value chain.

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Effect of Recycled Fine Aggregates Without Fines on Concrete Performance: A Circular Solution for Natural Sand Replacement

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Keywords: recycled fine aggregate, recycled concrete, partial sand replacement, waste valorisation, recycling

The construction industry is essential for urban development, driving the expansion of housing and infrastructure to meet the needs of a growing population. Nonetheless, this progress is accompanied by significant environmental challenges, particularly high consumption of natural resources on the production of concrete. In addition, infrastructure renewal and demolition generate construction waste, raising concerns about its management and storage, especially regarding its impact on the landscape and available space. This scenario underscores the urgency of adopting circular solutions that enhance alternative resource efficiency while supporting the continued advancement of the sustainable construction. The use of recycled concrete aggregates has emerged as a crucial strategy for fostering a circular economy and promoting sustainability within the construction sector. While much of the research has focused on recycled coarse aggregates, the recycled fine aggregate produced during recycling remains largely underutilized due to concerns regarding its inferior properties compared to natural sand. These limitations are primarily attributed to the high concentration of adhered cement paste, which negatively impacts the concrete's performances. However, this issue can be mitigated by removing the finest particles, thereby reducing the cement paste content and enhancing the desirable properties of recycled fine aggregates. This study explores the use of recycled fine aggregates without fines particles as a replacement for natural sand in concrete. The research focuses on the characterization of recycled fine aggregates by comparing three cases: recycled fine aggregate without fines (RFAWF), recycled fine aggregate (RFA), and natural sand (NS). One source of recycled aggregate and two samples of fines were removed from two distinct fractions (0/0.500 mm and 0/0.250 mm). Key parameters such as density, particle size distribution (PSD), water absorption, packing density, and cement paste ratio were evaluated. Concrete mixtures, replacing 50% and 25% of natural sand, were tested to assess their fresh properties (admixture demand, workability, air content, fresh density, setting time) and hardened properties (compressive strength and shrinkage). Furthermore, the mix design with 50% RFAWF was optimized to compensate for variations in packing density. Two potential solutions were proposed: adding a granular skeleton corrector or increasing the paste volume. The results indicate that removing the 0/0.500 mm or 0/0.250 mm fractions from the recycled fine aggregates results in lower water absorption. This positively influences the admixture demand for constant Slump compared to RFA. However it is always higher than the reference concrete made with NS. In addition, the study has showed that removing fines can reduce the packing density. The greater the quantity of fines is removed, the less dense the packing density of aggregate. The exclusion of fines results in lower packing density, due to the discontinuous particle size distribution (PSD). The recommended solution for improving slump and achieving better consistency is to incorporate corrective sand or increase the paste volume, ensuring the packing density remains similar to the reference concrete. Concrete mixtures incorporating RFA or RFAWF demonstrated compressive strengths comparable to those made with natural sand, provided that appropriate mix adjustments were made. The inclusion of a defoamer in the mix likely contributed to improved compressive strength by reducing air content in the recycled aggregate-based mixtures. Even with increased paste volume (higher water/binder ratio), no significant loss of compressive strength was observed. In terms of shrinkage behavior, concrete mixtures with RFAWF exhibited slightly better results compared to those with RFA. Reducing the replacement percentage of natural sand also helped minimize shrinkage. Furthermore, the use of RFAWF contributes to the circular economy by reducing construction waste and promoting the sustainable use of materials in the concrete industry. Regarding embodied CO_2,

the incorporation of recycled fine aggregates does not significantly impact the carbon footprint compared to the production of natural sand concrete. A life cycle assessment (LCA) approach should be employed to calculate the CO_2 levels, taking into account the reduction in transportation and quarrying activities, along with the energy consumption during processing. This assessment can further substantiate the environmental benefits of using recycled fine aggregates in concrete. Overall, this study highlights the potential of recycled fine aggregates as a viable alternative to natural sand in concrete production. Further research is recommended to optimize the production process and establish guidelines for widespread implementation in the construction industry.

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End-of-life analysis of silica aerogel-latex composites for building insulation.

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Keywords: Insulation material, Silica aerogel, Recycling, Life Cycle Assessment, Polymer.

Currently, the building sector is responsible for 36% of global energy consumption and 37% of CO_2 emissions, making it a key target for sustainability efforts. Silica aerogel is a low-density material composed of a solid porous network, making it an excellent thermal insulator used in the building industry, as it exhibits significantly lower thermal conductivity in comparison to traditional materials used for insulation. However, most silica aerogels lack the mechanical strength needed for use as a building material, in part due to their high porosity of up to 99%. Aerogels can be combined with reinforcing agents, such as polymers, which improve their tensile and compressive strength due to the crosslinking of polymer chains. Latex has been used as a binder for silica aerogels, which has also been found to significantly improve its mechanical strength while preserving most of its insulation properties, making it a feasible option for building insulation. However, there is little research on the circularity of such composite materials, which is crucial for sustainability goals. In part, this is because this material is very new, and there is no real-life data on its performance after several decades of use. Hence, this study aims to investigate several end-of-life (EoL) scenarios by performing accelerated aging of the composite, recycling or reusing it, and evaluating each approach by the quality of the resulting material, as well as the environmental impact of each method.

Two EoL scenarios are considered in this study, as depicted in Figure 1. First, the composite is chemically recycled by dissolution in a basic medium to extract silica, which is then used as a precursor for new aerogel synthesis. The latex remains solid and is collected and disposed of. This approach is expected to result in a higher quality product but also to have a higher environmental impact due to the need for raw materials and energy for the synthesis. The parameters for dissolution were chosen as follows: 1:10 solid-to-liquid ratio, 60 ºC, 2-hour reaction with 4M NaOH solution. The solution is then filtered, and HCl is added dropwise to precipitate silicic acid, which is dried and reacted again with NaOH in a Si:Na 1:2 ratio to obtain pure sodium silicate solution at 8 Si wt%. The solution is then passed through the ion-exchange resin, combined with 1 M ammonia as a catalyst, and gelled. The gel undergoes a series of solvent exchange steps and hydrophobization with TMCS and is dried via the ambient pressure drying method.

The second approach includes artificially aging the composite to represent a real-life scenario of 10-20 years in use and evaluating its performance. The aging conditions are established to be 50 ºC with 70% relative humidity, and the aging factor is calculated with the Arrhenius equation. The quality is expected to decrease, but not to the point of failure, based on prior research. Therefore, this material is then combined with a new composite in a certain proportion, and the properties are tested. The aim is to maximize the fraction of aged composite, while not compromising the quality of the product. The environmental impact is calculated, and the potential loss of insulation properties is evaluated by conducting a life cycle assessment (LCA) with a functional unit being the R-value of a new composite. This means that if, for example, the quality decreased by 10%, one would need more reused insulation material to achieve the same energy efficiency as if a new composite is used, which will increase its environmental impact of reuse. Then, the two scenarios are compared, and the most sustainable option is determined.

Preliminary results included aging the composite for an equivalent of 315 days (~11 months), after which the thermal conductivity decreased by 15%, and the water contact angle decreased by 3%. This is likely due to moisture adsorption, which can also cause changes in the silica aerogel network. Chemical recycling of the composite resulted in high-quality silica aerogel with a thermal conductivity of 18.3 mW/m·K and a water contact angle of 146.5 º. The composite was reacted without any milling, which was sufficient to extract the silica during the 2-hour reaction.

The results showed that both options are viable, and chemical recycling, while likely to have a higher environmental impact, is still important to consider since materials have a limited number of reuse cycles.

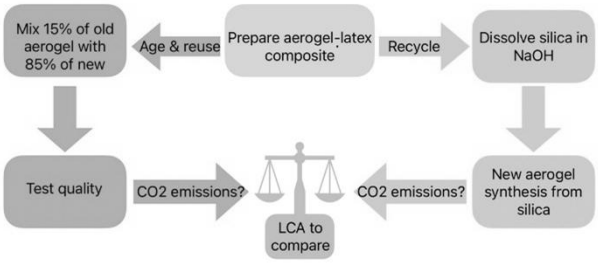

Figure 1. A schematic overview of the methodology.

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Environmental Toxicity of IBA-derived Permeable Blocks under Climate Change

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Keywords: Climate change, Leaching, Life cycle assessment, Incineration bottom ash, Permeable blocks.

Reusing incineration bottom ash (IBA) in permeable blocks offers potential for sustainable construction and urban stormwater management. This study evaluates the long-term leaching behavior of IBA-derived blocks under future climate conditions in Hong Kong, focusing on temperature projections of up to 35 oC and total precipitation reaching 600 mm annually over the next 15 years. Using the USEtox model, the study modifies the exposure factor to reflect changes in leaching dynamics. The findings show that under high temperatures (35 oC) and high L/S ratios, leaching rates of heavy metals, particularly chromium (Cr), exceed SPLP predictions, especially for blocks with higher IBA substitution ratios. The highest risk is associated with 100% IBA-derived blocks, where Cr mobility increases under warmer and wetter conditions. The study emphasizes the need to incorporate climate change impacts into life cycle assessments (LCA) of waste-derived construction materials. Recommendations include reducing the IBA substitution ratio in hot, humid regions to minimize risks. In contrast, higher IBA ratios may be suitable for cooler, drier areas. Long-term monitoring and risk assessments are critical for managing environmental and health impacts.

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Evaluating the Performance of Passive UHF RFID Tag for Traceability of Recycled Concrete Aggregates

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Keywords: Recycled concrete aggregates, Traceability, Digitalization, RFID technology, Circular construction

1. Introduction

The digital transformation of the construction industry is crucial for enhancing traceability, enabling real-time materials tracking, and ensuring that material quality is effectively communicated among stakeholders to support data-driven decision-making. As the largest consumer of raw materials, the construction industry contributes to about 8% of global CO2 emissions, necessitating adoption of sustainable material management strategies. One approach to mitigate adverse environmental effects is the incorporation of recycled concrete aggregates (RCA) in concrete production. However, their effective utilization is hindered by a lack of knowledge on the impact they have on concrete quality and performance. This knowledge gap can be bridged through digitalising their supply chain, enabling the tracking of their quality metrics to optimize concrete production and maintain structural performance.

2. RFID-based Traceability of RCA

Radio frequency identification (RFID) is a wireless and contactless technology that identifies and tracks objects through electromagnetic waves. In this study, passive ultrahigh-frequency (UHF) RFID technology is investigated to facilitate the tracking of RCA quality. Battery-free RFID tags with the ability to store information offer reliable traceability solutions. Despite its advantages, the performance of RFID tags is influenced by materials composition, signal attenuation, tag-reader orientation, and tag-to-reader distance.

Therefore, this study evaluates the reliability performance of an RFID tag embedded in RCA using readability distance (RD), received signal strength indication (RSSI), and tag read count (TRC) as key performance indicators. RD measures the maximum distance at which tags can be read, reflecting the RFID system's effectiveness for diverse operational conditions. RSSI quantifies the backscattered power received by the reader from the tag, which serves as the indicator of signal efficiency and communication of the system. TRC, reflecting the number of successful reads per second, offers a measure of detection stability and the system's robustness. The relationship between components of the RFID system and their association with the material database to facilitate traceability is represented in Fig. 1.

3. Selected RFID System

An RFID tag with distinct antenna dimensions of 10 mm x 8 mm x 5 mm was selected to investigate identified challenges. The tag was equipped with Alien Higgs-3 chips, operating within the EU RFID frequency range of 865-868 MHz, compliant with the European Telecommunications Standards Institute (ETSI), and IP68 rating. The performance evaluation of the tag utilized the Chainway R6 UHF RFID sled reader, which features a Cortex-M3 MCU (microcontroller unit) and a 4 dBic circular polarized antenna, ensuring high sensitivity, robust performance, multi-tag reading capabilities, and data collection from tags. It operated within the EU frequency range, supporting C1 GEN 2 / ISO 18000-6C protocols and at an output power level of 30 dBm.

4. Methodology

The tag was embedded in RCA at depths of 10 cm, 20 cm, 30 cm, and 40 cm to simulate the effect of material composition and chances of displacement of the tag's position due to the granular nature of the material. The RD, RSSI values, and TRC were measured by moving the RFID reader away from the aggregates at an increment of 20 cm with one second operational time at each position. The angular orientation between the reader and tag was varied at 30-degree intervals to evaluate the influence of angular positioning on the selected RFID system's performance.

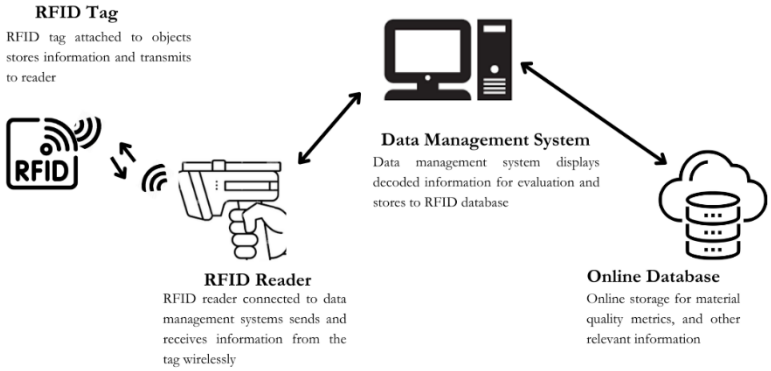

Fig. 1. Schematic representation for RFID-based traceability system

5. Results

The selected tag performed well across all test conditions, though variability in RD, RSSI, and TRC was observed. At the depths of 10 cm and 20 cm, this tag has maintained readability distances ranging from 80 cm to 120 cm, with RSSI values ranging from -60 dBm to -78 dBm, and the read rate varying between 9 to 14 per second depending on the angular orientations. At the depth of 30 cm, the tag performance began to reduce, and at 40 cm depth, it achieved maximum readability of 90 cm with an RSSI of -77 dBm and a read rate of 10 per second at an aligned angle of 0-degree. At the same depth, the minimum readable distance was 50 cm, observed at a misaligned angle of 240 degrees, with an RSSI of -79.1 dBm and a read rate of 6 per second. The measured RD, RSSI, and TRC values for the tag at a depth of 20 cm are represented in the Fig. 2.

6. Conclusion

The results of the study confirm that the performance of the RFID system varied with the change in tag-reader orientation and an increase in the tag-to-reader distance, while the tag remained detectable across all tested conditions. These findings demonstrated the feasibility of RFID technology for automated RCA quality tracking, supporting the digitalization of the circular construction process.

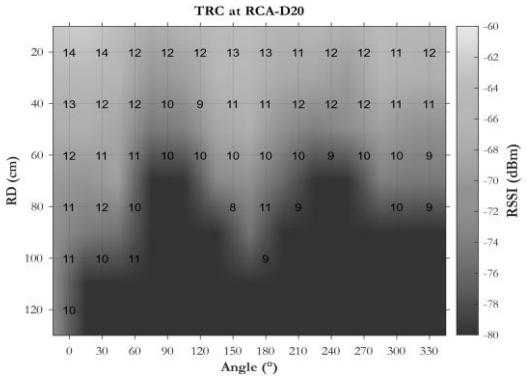

Fig. 2. Signal intensity of selected RFID system with RD, RSSI, and TRC values at 20 cm RCA depth

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Evaluating the Suitability for Use as Concrete Aggregate of Excavated Rock Types from the Einstein Telescope Project (Euregion Meuse-Rhine)

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Keywords: Einstein Telescope, aggregate, sustainability, petrography, tunnelling

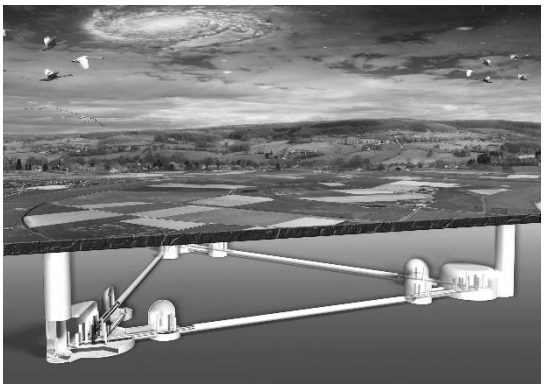
The Einstein Telescope (ET) project is an ambitious initiative aimed at constructing Europe's most advanced underground observatory for gravitational waves. The Euregion Meuse-Rhine (EMR) is one of the three candidates for this project, with a feasibility study expected to be completed by the end of 2026. The project involves creating a 30-kilometer tunnel network at a depth of 200-300 meters. At present, a major geological subsurface mapping survey is conducted for tunnel siting, design and construction purposes involving drilling campaigns and detailed outcrop studies. A crucial aspect of the project is its sustainability, particularly the maximal use of the excavated material as concrete aggregates for both the ET infrastructure and local markets.

This contribution involves a comprehensive petrographic, geochemical, and geomechanical characterization of borehole and outcrop samples from each relevant lithology. The potential of these excavated materials to meet concrete aggregate product requirements is evaluated. To ensure sufficient sample volumes for aggregate testing, outcrop analogue materials from nearby quarries and outcrops are selected for their similarity to the drill core materials. The selection process targets representative materials for the planned excavation, considering geological variability from Upper Devonian Famennian sandstones to lower Carboniferous Namurian shales. Representative samples from outcrops are being sampled and characterized for aggregate properties. Tests include methylene blue (EN 933-9), water absorption (EN 1097-6), Micro-Deval abrasion resistance (EN 1097-1), Los Angeles fragmentation resistance (EN 1097-2), freeze-thaw resistance (EN 1367-1), and ASR susceptibility (EN 12620).

Preliminary results indicate varying degrees of suitability of the selected materials as concrete aggregates. Some intervals of the Upper Devonian sandstones, such as the Montfort-Evieux Formation, and lower Carboniferous limestone, such as the Lives Formation, are already being exploited in several quarries to produce high-quality concrete aggregate in Southern Belgium. However, some stratigraphic intervals present more challenging lithologies, including shales. These shales, characteristic of the Namurian, but also present within the Famennian sandstones, primarily consist of micaceous clay-silt rock and are frequently interbedded with fine micaceous green-gray sandstones and quartzites. The potential use of these mixed intervals is crucial to assess.
The subsurface of the ET-EMR study area is strongly affected by tectonic processes, including brittle and ductile deformation, leading to highly competent rocks with high UCS values, low water absorption and good abrasion and fragmentation resistance. The effect of rock deformation on aggregate properties, especially its alkali-silica reactivity (ASR), is being assessed in relation to petrographic observations and characterization of quartz microstructural deformation. Features like undulatory extinction, deformation bands, and sub-grains in quartz tend to increase the surface area and the number of reactive sites, making the quartz potentially more susceptible to ASR.

This study will ultimately provide an exhaustive rock typing of all lithologies potentially encountered during drilling, with a thorough characterization of their petrographical, geomechanical, and essential

characteristics for intended use as concrete aggregate. By identifying suitable materials for use as construction material feedstock, the study contributes to a more sustainable development of the ET infrastructure by minimizing the environmental impacts related to disposal of waste materials or extraction of natural resources. This research will refine the understanding of the aggregate potential of various lithologies, ensuring the optimal implementation of the Einstein Telescope project. Upon refining the geological model and the telescope's exact location, the study will enable quantification of the tonnage of recoverable materials available for on-site aggregate use, ensuring accurate resource planning and sustainable construction practices.



Artist Impression of the Einstein Telescope, by Marco Kraan (Nikhef).

Evaluation of Washing Pre-treatment on the Mechanical Properties and Environmental Performance of Phosphogypsum-Based Cemented Paste Backfill

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Keywords: Phosphogypsum, washing pre-treatment, Phosphogypsum-based Cemented Paste Backfill, Life-Cycle assessment.

Phosphogypsum (PG)-based Cemented Paste Backfill (PCPB) is an effective solution to manage the large volume of PG stockpiles. However, challenges such as the high fluoride content, uneven particle size distribution, and insufficient strength of PCPB specimens limit its application in the backfilling field. This study investigated the impact of different washing conditions (number of washings and washing ratios) on the properties of PG. Specifically, it analyzed the changes in particle size distribution of PG, fluoride leaching characteristics, and mechanical properties of PCPB specimens after pre-treatment. The results demonstrated that washing pre-treatment significantly changed the particle size distribution of PG, promoting the formation of finer particles and the strength of PCPB specimens. And the column leaching tests, realistically simulating the conditions of PCPB specimens in underground environments, confirmed that washing effectively reduces the fluoride content. Additionally, this study incorporated Life-Cycle assessment analysis to quantitatively assess the carbon emissions associated with the process. The above results provide valuable theoretical support for the resource utilization of PG and a novel approach for the pre-treatment of multiple solid wastes.

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Exploring Lightweight Blocks Using Wheat Straw and Recycled Concrete Fines through Carbonation

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Keywords: accelerated carbonation, carbonation curing, recycled concrete fines, natural fibres, properties

The construction sector contributes significantly to global carbon dioxide (CO_2) emissions, with concrete alone accounting for approximately 8% of the total. Given the increasing demand for sustainable construction materials, this study explores the integration of Recycled Concrete Fines (RCFs) and Natural Fibers (NFs) into lightweight cement-based blocks, with a focus on utilizing carbonation curing to enhance both environmental performance and material properties.

RCFs, a byproduct of concrete recycling, are fine particles obtained from the multiple crushing of demolished concrete which mainly consist of hydrated cement paste and fine aggregates, making it rich in residual cementitious content. However, their reuse is limited due to variability in composition, high water absorption, and agglomeration, which can negatively affect the workability, strength and durability of fresh mixes. This often leads to landfilling or low-grade downcycling. Similarly, agricultural waste like wheat straw presents an abundant, renewable, and biodegradable resource for construction materials. When integrated into cementitious composites, NFs contribute to reduced density and improved thermal insulation but can also increase porosity, potentially compromising the material's strength and durability. This study aims to combine these underutilized resources to create lightweight, sustainable concrete blocks.

The experimental methodology focused on varying the RCF content (replacement of cement by mass) while maintaining a constant NF dosage. All mixes were designed with the same water-to-binder ratio. Samples were subjected to two carbonation curing temperatures (ambient and high temperature), under controlled CO_2 concentration and relative humidity for three days. Each mix was tested in both carbonated and non-carbonated states, resulting in eight total conditions. Samples were evaluated at 7 and 28 days for flexural strength, compressive strength, density, porosity, thermal conductivity, and microstructural characteristics via Thermogravimetric Analysis (TGA), Fourier Transform Infrared Spectroscopy (FTIR), pH test and optical microscopy.

By systematically exploring the influence of three factors - mix composition (RCF content), carbonation state (non-carbonated or carbonated), and curing temperature (ambient or high temperature) - this research seeks to address the gap in the reuse of RCF in building materials.

Results showed that carbonation curing, particularly at higher temperature, significantly enhanced material performance. The formation of calcium carbonate ($CaCO_3$) densified the matrix by filling internal voids and reducing porosity, leading to higher flexural and compressive strengths as well as higher bulk density and thus higher thermal conductivity. In contrast, non-carbonated samples displayed lower strength but higher thermal efficiency due to retained porosity and limited matrix densification.

Thermal and microstructural analyses supported these findings. TGA and FTIR confirmed the conversion of hydration products (calcium silicate hydrate (C-S-H), ettringite, and portlandite) into $CaCO_3$, with higher-temperature carbonated samples displaying peaks characteristic of highly crystalline calcite. The reduction of hydroxyl bands and the emergence of carbonate-specific signals further validated carbonation

effectiveness. Microscopy revealed visibly denser structures in carbonated samples compared to their non-carbonated counterparts.

The role of RCFs was twofold, as the porous structure and active areas enhanced CO_2 diffusion, increasing carbonation depth and promoting matrix densification, particularly at higher curing temperatures. As a result, strength gains in carbonated samples increased with RCF content. However, in non-carbonated mixes, RCFs had minimal influence on mechanical performance, indicating that their primary benefit lies in facilitating carbonation rather than contributing to hydration-driven strength development.

Elevated curing temperature played a pivotal role in accelerating carbonation and improving performance. Enhanced CO_2 diffusion and reaction kinetics at higher temperature led to deeper carbonation and more complete conversion of hydration products to $CaCO_3$. However, this also caused early hydration to occur, limiting long-term strength development due to the depletion of reactive materials. Despite this, the combination of high temperature and RCF inclusion resulted in the best overall mechanical performance among all tested conditions.

In summary, this study demonstrates that a strategic combination of carbonation curing, RCF content optimization, and elevated temperature can transform construction and agricultural waste into sustainable, well-performing building materials. The resulting lightweight blocks are particularly suitable for non-load-bearing applications, contributing to the decarbonization of the construction industry. Given that RCFs are still largely landfilled and wheat fibers are an abundant agricultural byproduct, this research offers an innovative pathway for their reuse in construction applications. Moreover, it contributes to the knowledge on incorporating waste materials into lightweight cement-based products, supporting efforts to reduce environmental impacts and promote circular economy practices in construction.

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Impact of Recycled Cement Factory Kiln Masonry as Aggregate in Cement Mortars

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Abstract:
The refractory linings in cement factory kilns are typically replaced every 10 years, which necessitates the identification of sustainable solutions for managing the resulting refractory brick waste. Refractory linings are composed of various types of refractory bricks, including alkali-resistant, magnesia, alumina bricks etc. each designated for specific zones within the kiln. The properties of these bricks, such as density, fire resistance, and alkali resistance, vary significantly. Upon replacement of the refractory lining, the used bricks can be categorized into two groups: intact bricks, which may be reused in construction, and damaged or waste bricks, which require recycling. This study investigates the potential utilization of refractory brick waste from the kiln preheating zone as fine aggregates in cement mortars.

Keywords: Refractory bricks, brick sand, cement mortar, recycled aggregate

Methods:
This study is analogous to previous research in which recycled silicate masonry was utilized as an aggregate in cement mortars [1] and is structured into four distinct phases.
In the first phase, tests are conducted on the raw materials (refractory bricks). Characterization of these raw materials includes X-ray fluorescence (XRF) and scanning electron microscopy (SEM) analyses to identify the material composition, as older kilns often lack classifications for the bricks of their refractory linings. Additionally, density and water absorption are measured to further differentiate the material properties. The fine aggregates are processed using a jaw crusher, with particles in the 0/4 fraction are separated using sand sieves. Larger particles are subsequently crushed further in the jaw crusher, and the process is repeated until the desired particle size is obtained.
In the second phase, recycled fine aggregates are characterized by determining their bulk density, absolute density, water absorption, and grain composition.
The third phase involves the preparation of dry mixtures, followed by testing of the cement mortars. A total of 15 different mixtures were prepared, with two primary criteria for variation: the proportion of fine aggregate replaced by silica sand (0, 25, 50, 75, and 100%) and amount of superplasticizer added to dry mixtures. The laboratory tests during this phase primarily focused on the rheological properties of the mixtures.
In the fourth and final phase, the mechanical properties and water absorption of the cement mortars are measured. The mechanical tests include measurements of flexural strength, compressive strength, tensile strength and pull-off adhesion.

Results:
Results indicate that the bulk density of brick sand was 1303 kg/m³, while silica sand had a bulk density of 1491 kg/m³. The primary difference in bulk density can be attributed to variations in material porosity. The water absorption of silica sand (grain) according to previous studies is approximately 0.1%, while the measured water absorption of refractory brick sand was significantly higher, at 2.73%. Despite its higher bulk density, silica sand has an absolute density of approximately 2650 kg/m³, while the refractory brick

sand studied exhibited an absolute density of 2820 kg/m³.
To facilitate a comparison of the results, a flow table test was performed on all 15 mortar mixtures. The water-to-dry material ratio was changed and measured to get equal spread of 150 mm ± 2 mm for all mortar mixture samples. The range of water-to-dry material ratio varied based on plasticizer and brick sand proportion in mortars. Furthermore, viscosity loss over time was monitored. The results indicated that as the proportion of brick sand increased in the mortars, a higher water demand was required to maintain the same viscosity. Additionally, the viscosity loss occurred at a faster rate in mortars with a higher percentage of brick sand.
Mechanical properties of the cement mortars are yet to be measured and evaluated in the current phase of the research. All mortar specimens have been prepared, conditioned, and will be tested after 28 days. The remaining results will be presented in the full paper.

Conclusion:
This study was conducted to evaluate how recycled refractory masonry as fine aggregate influences properties of cement mortars. Early results indicate that brick sand shows potential for use as fine aggregate in cement mortars. However, it is premature to draw definitive conclusions at this stage, as the mechanical properties have not yet been measured or evaluated.

Acknowledgement:
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Incorporation of Shredded Wind Turbine Blade Waste in Concrete Using a Packing Approach

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Keywords: Shredded wind turbine blade (SWTB), End of Life (EoL), Andreasen and Andersen Model (A&A), Concrete, Strength

Wind energy plays a vital role in sustainable energy production. However, the end-of-life (EoL) management of wind turbine blades has emerged as a critical environmental challenge. Wind farms built in the late 20th century have started to generate large quantities of composite waste due to the 20–25 year service life of wind turbines. This waste generation is expected to accelerate in following decades, posing a significant challenge for sustainable waste management.

End-of-life (EoL) solutions for the two main components of wind turbines: the metallic body (including the motor) and the wind turbine blades (WTB), should be considered separately. The motor and the metallic body of wind turbines can be recycled and reused. However the composite structure of the WTB, which consists of thermoset polymers and glass or carbon fibers, presents challenges in recycling. This leads to an accumulation of WTB waste (WTBW) in landfills at their end of life. With its production capacity and significant raw material demand, concrete provides a valuable opportunity for the sustainable utilisation of rapidly accumulating WTBW. To utilize WTBW in concrete, a suitable recycling process must be implemented. Various recycling approaches are available for WTBW, including thermal, chemical, and mechanical methods. Among these, mechanical recycling is generally preferred due to its lower energy requirements and practicality. This method involves cutting the blades into smaller pieces and subsequently crushing them into finer particles. However, shredded wind turbine blades (SWTB) exhibit a highly heterogeneous particle size and morphology, consisting of a mixture of fine powders, micro- and macro-sized fibers, and irregular flakes. SWTB can be utilised in concrete for fiber reinforcement or partial substitution of cement or sand. However, this requires detailed sorting of the waste, limiting the usable portion to specific fractions.

In this research SWTB is used as an overall component in concrete. For this, a new concrete mix design is created using two methods. The Anderson and Andreasen (A&A) model, that is based on particle packing and as a complementary approach, the American Concrete Institute (ACI) method is also applied. The SWTB is a material composed of both powder and fibres, and it also has a high water absorption. Thanks to the new approach with modifying the A&A method, all of these characteristics are taken into account during the concrete design. The model is modified to optimize whole mixture including aggregate and powder replacement and fiber reinforcement with utilizing the SWTB.

The SWTB, ranging from 0.63 μm to 10 cm in size, is composed of 51% granular particles and 49% micro to macro fibers and flakes, enabling its dual role as both an aggregate replacement and a fiber reinforcement. Concrete mixtures were prepared with 0%, 1%, 3%, and 5% SWTB by its total mass, corresponding to 0–2.7% fiber content, 0–10.2% aggregate replacement, and 0–4.4% cement replacement by volume.

The prepared samples were evaluated based on both their fresh and hardened properties, including slump, air content, and density, as well as compressive strength, splitting tensile strength, elastic modulus, and flexural performance with crack mouth opening displacement (CMOD). The use of SWTB, especially at higher dosages, led to a decrease in slump. As the amount of SWTB increased, the air content of the concrete slightly decreased; however, the fresh density also dropped. This reduction in density is mainly due to the low specific density of SWTB.

With the use of the modified A&A method in the mix design, the concrete retained a high level of strength even with increased SWTB content. The 28-day compressive strength of the control sample was 57.2 MPa, while the mixture containing 5% SWTB still achieved 50.8 MPa, indicating that the reduction in strength was relatively small. Elastic modulus at 28 days is also decreased relatively from 39.6 GPa to 30.9 GPa. The effect of fibrous part of SWTB also assessed by the split tensile and CMOD tests. The 28-day splitting tensile tests showed that the control sample had the highest strength at 4.2 MPa. For the SWTB mixtures, strength tended to increase with higher SWTB content, and the 5% SWTB sample reached 3.7 MPa, with only a limited reduction compared to the control. Although the irregular and damaged surfaces of SWTB fibers limit their bonding with the cement matrix, CMOD flexural tests confirmed that SWTB contributes to fiber reinforcement in concrete.

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Indirect Mineralization of Steel Slag via acetic acid as Cement Replacement materials

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Keywords: Steel Slag, Mineralization, Carbonation, cement replacement.

The cement industry is a significant contributor to global CO2 emissions, accounting for over 5% of anthropogenic emissions. The application of supplementary cementitious materials (SCMs) represents a viable solution to partially substitute Portland cement, which not only provides economic and environmental benefits by repurposing industrial waste, but can also enhance the mechanical and durability properties of the end product. Carbon mineralization is a thermodynamically favourable process that enables effective CO_2 capture, storage, and utilization while simultaneously enhancing the properties of construction materials. Among industrial by-products, steel slags—particularly basic oxygen furnace (BOF) slag and electric arc furnace (EAF) slag—are highly rich in calcium and exhibit significant potential as supplementary cementitious materials. However, the low inherent reactivity and heavy metal concerns of raw steel slags limit their direct application in cementitious systems. To address these challenges, this study systematically investigates the indirect carbonation of steel slags under hydrothermal conditions, aiming to enhance their mechanical performance and environmental safety for sustainable cement applications.

In this work, EAF and BOF slags were pre-ground and sieved to achieve a particle size of less than 1 mm, ensuring uniform reactivity during carbonation. The sieved slags were then subjected to hydrothermal carbonation in a reactor using an acetic acid-to-water ratio of 0.24:1, maintained at 105 °C under 10 bar CO_2 pressure for 4 hours. After carbonation, the residues were filtered, dried at 105 °C, finely ground to pass through a 75 μm sieve, and subsequently sintered at 350 °C for 2 hours to promote the decomposition of calcium and magnesium acetates into carbonates. Chemical analysis revealed that the raw slags were characterized by high CaO and MgO contents, with relatively low levels of SiO_2 and Al_2O_3. EAF slag, in particular, displayed a significantly higher Fe_2O_3 content compared to BOF slag. The carbonation experiments showed that the carbonation efficiency notably increased from 2.45% in water at 80 °C to 7.13% in acetic acid at 105 °C, emphasizing the catalytic role of acetic acid in promoting slag dissolution and carbonation reactions.

Mineralogical characterization demonstrated that the RO phase in EAF slag remained highly stable throughout the carbonation process, whereas phases such as C_2S and C_2F dissolved significantly under the hydrothermal acidic conditions, promoting the formation of calcite and carbonates after subsequent heat treatment. Most of the Si and Al components were found to remain in an amorphous phase. Following calcination at 350 °C, Ca/Mg acetates decomposed effectively to form fine-grained carbonates, while iron-rich minerals persisted uncarbonated, often accompanied by the accumulation of heavy metals. Hydration heat flow studies revealed a marked retardation of the induction period for raw EAF slag, attributed to the presence of stable RO phases and acetates. When carbonated products were used to partially replace cement, the hydration heat was significantly reduced compared to the reference ordinary Portland cement (OPC) system. Importantly, carbonated slag showed a remarkable improvement in compressive strength relative to the raw slag. At a 50% cement replacement level, the compressive strength of mortars containing carbonated slag achieved up to 80% of the strength of the OPC control. The performance difference

between BOF and EAF carbonated slags was attributed to the lower RO phase content in BOF, resulting in higher reactivity.
Beyond mechanical performance, environmental benefits were also observed. Heavy metal leaching was significantly reduced in the carbonated slag compared to the raw material, greatly enhancing the environmental safety of the developed binders. In addition to conventional cement hydration products, carbonated slags contributed supplementary phases such as finely dispersed calcite and unreacted RO phases, with higher quartz crystallinity observed in non-carbonated EAF and BOF residues.

Overall, this study establishes a robust process framework for the indirect mineralization of steel slags through hydrothermal carbonation, leading to a dual benefit of material performance enhancement and environmental risk mitigation. The findings underscore the promise of combining indirect carbonation techniques with waste valorization strategies to produce next-generation low-carbon construction materials, contributing meaningfully to circular economy practices and the urgent global need for sustainable building solutions.

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Influence of Jaw Angle in Smart Crushing on Selective Recovery of Recycled concrete fines

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Recycling of concrete is essential to reduce the environmental impact of the construction industry. While recycled aggregates are widely reused, the reusability of recycled cement fines remains limited due to challenges in separation and quality control. The Smart Crusher technology introduces a mechanical innovation aimed at selectively separating hydrated cement paste from natural aggregates during concrete recycling. However, the crushing performance depends significantly on the mechanical configuration of the crusher, particularly the jaw angle.
This study evaluates the effect of two configurations of the moving jaw (Angle 1: 90° and Angle 2: 85°) on the quantity and quality of the recovered fines from concrete. Key crusher parameters such as jaw distance and speed were held constant. The crushed output was evaluated through sieve analysis, ultrasonic particle size distribution (PSD), thermogravimetric analysis (TGA), X-ray fluorescence (XRF), and X-ray diffraction (XRD).
Results showed that Angle 2 (85°) promoted greater size reduction, producing a higher quantity of fines by fragmenting both the cement paste and natural aggregates. While this resulted in a higher yield, the fines exhibited higher SiO_2 content, indicating increased quartz contamination and reduced selectivity. In contrast, Angle 1 (90°) was more selective, yielding fewer fines but of higher quality, with lower SiO_2 and higher CaO content, suggesting better preservation of cement paste and reduced aggregate breakdown. These findings were supported by XRD analysis, which revealed reduced quartz and higher Portlandite peaks in samples crushed with Angle 1, further confirming the improved separation of cementitious phases.
The findings underscore a clear trade-off between quantity and quality. While Angle 2 is more effective in size reduction and yields a higher volume of fines, it increases the risk of unwanted aggregate crushing and results in lower material purity. In contrast, Angle 1 is more selective, producing fewer fines but with higher cementitious quality, making it preferable for applications that prioritize reactivity and purity, such as binder reuse or use as supplementary cementitious material. These conclusions are supported by XRD analyses, which showed more pronounced Portlandite peaks in Angle 1 samples, while Angle 2 samples were dominated by quartz and calcite. Additionally, TGA confirmed a higher calcium hydroxide content in the fines from Angle 1, reinforcing the evidence of better preservation of hydrated cement compounds.
This study contributes valuable data for optimizing mechanical recycling parameters in circular concrete technology.

Keywords: Concrete recycling, cement paste recovery, jaw angle, Smart Crusher, recycled concrete fines.

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Influence of recycled concrete aggregate in high-performance concrete on its selected properties

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Keywords: RCA, high-performance concrete, mechanical properties, sustainability, thermal stress

The construction industry is one of the largest consumers of natural resources and one of the main producers of construction waste. In recent years, more sustainable solutions have been increasingly promoted, including the recycling of concrete waste and its reuse as aggregate in new concrete composites. Recycled concrete aggregate (RCA) is an environmentally friendly alternative to natural aggregates and its use can significantly reduce the consumption of feedstock and limit the negative environmental impact of the construction industry. The greatest challenges in replacing natural aggregates with recycled aggregates are faced by high-performance concrete (HPC), which is characterized by its exceptional strength, durability and low porosity. RCA has different physico-mechanical properties compared to natural aggregate, in particular higher water absorption and lower strength characteristics, which can negatively affect the final properties of HPC. Therefore, the effect of replacing natural aggregate with RCA on the properties of HPC needs to be thoroughly analysed.

The aim of this study is the experimental evaluation of selected physical-mechanical properties of high-performance concrete with partial and complete replacement of natural aggregate by RCA. So far, three variants of HPC have been subjected to laboratory tests: reference HPC without RCA aggregate replacement, HPC with 15% replacement of natural aggregate by RCA, HPC with 30% replacement of natural aggregate by RCA. The composition of the HPC consisted of cement CEM I 52.5 R, silica fume, limestone, sandstone aggregate 0-4 mm, granite aggregate 4-8 mm, plasticizers based on polycarboxylate ether and polycarboxylate and modified phosphonate and water. The sandstone aggregate was replaced by RCA with a granulometry of 0-4 mm. The water ratio for all mixture was kept at 0.23.
Testing focused on monitoring the development of compressive strength and flexural strength over time. In the next phase of the research, tests of mixtures with 50% and 100% replacement of natural aggregate by RCA are being prepared, which will be subjected to: compressive strength and flexural strength tests, determination of the dynamic modulus of elasticity by ultrasonic method and observation of microstructural changes after exposure to high temperatures. The development of the strength characteristics over time will also be carried out on the 50% and 100% RCA aggregate replacement mixtures.

Preliminary results (bar chart in Figs. 1 and 2) show that at 15% and 30% replacement of natural aggregate with recycled aggregate, there was a slight decrease in the flexural strength of HPC with increasing proportion of RCA. In terms of compressive strength, the samples with 15% RCA replacement reached the highest values after 28 days, while the samples with 30% RCA replacement dominated after 56 days. At this point, it is worth mentioning the considerable variance of the values, which negatively affected the results. At higher levels of RCA replacement, a more pronounced effect on the mechanical properties is expected, as recycled aggregate has lower strength characteristics and greater porosity compared to natural aggregate. An important aspect will be to monitor the dynamic modulus of elasticity, as higher porosity leads to a reduction in material stiffness. In addition, the planned experiments with exposing the concrete to thermal stress will provide important insights into the thermal behaviour of HPC with RCA, which may be crucial for its use in demanding construction applications.

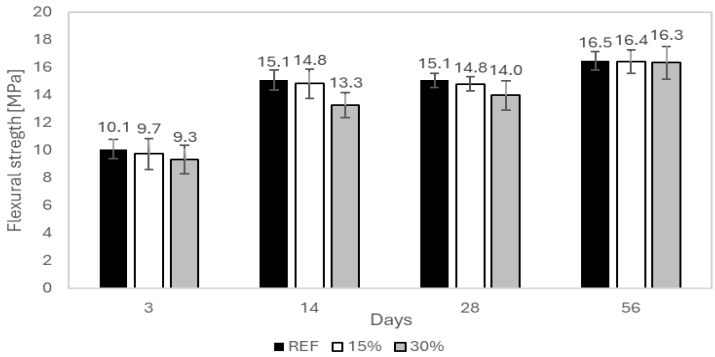

Fig. 1 Bar chart of development of flexural strength in time

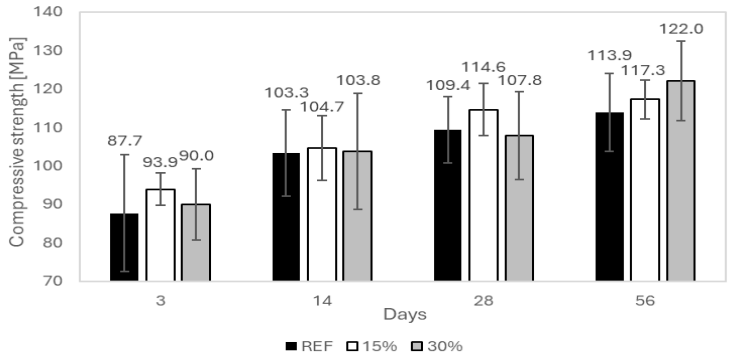

Fig. 2 Bar chart of development of compressive strength in time

The results so far indicate that recycled aggregate can be used as a partial replacement of natural aggregate in high-performance concrete without a significant negative impact on its strength characteristics. This opens up the possibility of a wider use of RCA in HPC, which can reduce the environmental footprint of concrete structures and promote the sustainability of the construction industry without significantly altering its properties. In the next phase of research, the effect of higher RCA replacement on the mechanical and microstructural properties of HPC will need to be analysed in more detail, and it is hoped that the results of the experiments will provide a more comprehensive view of the potential use of recycled aggregate in HPC.

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Lime-zeolite mortars for repair of historical buildings

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Keywords: Lime mortar, zeolite, lightweight aggregate, porosity, durability.

The protection of historic buildings requires the use of traditional building materials that are as compatible as possible with the historic materials. Air lime mortars are not suitable for use in damp environments due to their non-hydraulic properties and low frost resistance. The use of natural hydraulic lime (NHL) renders is therefore often preferred for renovation purposes. Significant changes in the properties of air lime mortars can be achieved by the addition of pozzolanic admixtures or aggregates with pozzolanic properties. In the past, the most used natural pozzolanic materials were crushed bricks, ceramics, volcanic ash, lava and pumice, which are still often used in conservation rendering. Porous aggregates with pozzolanic properties can improve not only the mechanical properties of mortars, but also their ability to accumulate salts from the masonry, frost resistance and the transport of liquid water from damp masonry. The use of a combination of finely ground natural zeolite as a binder substitute and at the same time the lightening of lime mortars with coarse natural zeolite has not yet been the subject of any research. For this reason, the paper aims to describe the effects of partial lime replacement with finely ground natural zeolite on the mechanical, microstructural and durability properties of air lime mortars lightened with coarse natural zeolite that meet the functional and technical criteria imposed on repair mortars.
Mortars were prepared with 40% lime replacement by fine zeolite, quartz sand replacement by coarse zeolite of the same granulometry and a combination of these two replacements and their fresh properties (bulk density, air content, water retention), compressive and flexural strengths, porosity, water absorption, capillary water suction, frost resistance, and salt crystallization resistance were compared with the reference lime mortar. The natural zeolite used had a Chapelle pozzolanic activity 729 mg $Ca(OH)_2$/g after 1 day treatment and 1395 mg $Ca(OH)_2$/g after 5 days treatment, similar to that of pumice or metakaolin, and it was therefore expected to improve the mechanical properties and durability of lime mortars.
The addition of fine zeolite to lime mortars resulted in a reduction in the amount of mixing water required to produce mortars with the same workability. The porous character and water absorption of zeolite led to an increase in water retention in mortars. Although a higher water retention would not directly affect any of the properties studied, it may be beneficial to the durability of the material by retarding the initial drying, thus reducing the development of drying shrinkage cracks. The air content in mortars was significantly increased in mortars with coarse zeolite. The use of light zeolite aggregate in the composition of mortars led to their higher porosity, lower density, improved capillary suction and water absorption, and increased salt accumulation, while the replacement of lime with fine zeolite resulted in an increase in the strength and frost resistance of the prepared mortars. Mortars with a combination of replacing part of the lime with fine zeolite and sand with coarse zeolite showed the best mechanical properties at all times monitored. The resistance of the mortars to salt crystallization using Na_2SO_4, NaCl and NH_4NO_3 solutions was improved by the addition of zeolite, although the mortars had relatively low resistance to the Na_2SO_4 reaction, which formed gypsum and calcium sulfoaluminates, dramatically disturbed the structure of the mortars.
In terms of compatibility, functional and technical criteria, lime-zeolite lightweight mortars can be classified as repair mortars, particularly suitable for dewatering and desalinating of masonry. An undeniable advantage of these mortars is their lower carbon footprint compared to lime or NHL mortars.

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Long Term Compressive Strength of Concrete made with Ceramic Wastes as a Partial Substitute for Cement and Fine Aggregates

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Keywords: ceramic, compressive, replacement, validation, waste

In response to growing environmental concerns associated with cement production and natural aggregate extraction, this study explores the potential of ceramic waste (CW) as a sustainable and effective partial substitute for both cement and fine aggregates in concrete. The research contributes to the state of the art by addressing the long-term mechanical performance of concrete modified with ceramic waste—an area previously underexplored. Recognizing that conventional cement production contributes up to 8% of global CO_2 emissions, this study underscores the importance of utilizing industrial by-products such as ceramic tile waste to promote sustainable construction and support circular economy practices.

A two-stage experimental methodology was adopted, comprising an Initial Experiment (IE) and a Validation Experiment (VE). The IE was conducted about 9 years ago, and although long term results were observed, this was not the primary objective of the research. VE was recently conducted to confirm the results obtained during the IE, and further explore long term results. The optimized test mix, referred to as 16CC50CS, contained 16% ceramic waste powder (CWP) replacing cement (CEM I) and 50% crushed ceramic sand (CS) substituting natural fine aggregates (crusher sand). Both experiments were designed to evaluate compressive strength performance over extended curing periods, with the VE extending testing up to 270 days. Materials were carefully sourced and processed to ensure compatibility, including matching the particle size distribution of ceramic sand to that of natural aggregates and ensuring uniform fineness of the ceramic powder. Concrete was mixed, cast into standardized cubes, and cured under controlled conditions, followed by compressive strength testing at specified intervals.

The results revealed a consistent and substantial increase in long-term compressive strength in CW-modified concrete. While the control mix exhibited superior early-age strength in the IE, the 16CC50CS mix demonstrated marked improvements over time, achieving 54.5 MPa at 28 days compared to the control's 44.4 MPa. These trends were even more pronounced during the VE, where the 16CC50CS mix outperformed the control at all stages, reaching 69.7 MPa at 270 days versus 51.8 MPa for the control. This improved performance is attributed to continued pozzolanic activity, enhanced particle packing, and a denser microstructure facilitated by the fine ceramic particles. The mix also demonstrated sustained strength development beyond 28 days, highlighting the long-term benefits of CW substitution.

These findings affirm that processed ceramic waste, when used in optimal proportions, significantly enhances the mechanical durability and strength of concrete. Beyond strength performance, the substitution of ceramic materials also contributes to reduced environmental impact through waste repurposing and decreased reliance on energy-intensive cement production. Importantly, the study confirms the reproducibility of these results across different aggregate sources and test conditions, reinforcing the practical viability of ceramic waste integration in conventional concrete applications.

In conclusion, the research validates the long-term structural benefits of using ceramic waste as a dual replacement material in concrete production. The superior strength development, coupled with

environmental and economic advantages, positions ceramic waste as a promising candidate for sustainable construction. Further research is recommended to explore the application of CW-based mixes in high-performance concrete and to evaluate their behaviour under diverse environmental and structural loading conditions.

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Mechanochemical-calcination of Australian natural clays for low-carbon cement binders

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Keywords: Australian natural clay; Cementitious materials; Calcination; Mechanochemical activation; Compressive strength

1 Introduction

Cement production is a major contributor to global CO_2 emissions. Supplementary Cementitious Materials (SCMs), such as calcined clays, have emerged as a sustainable alternative to reduce clinker consumption. This study explores a combined activation process that integrates calcination and mechanochemical activation to enhance the reactivity of natural clays, including kaolinite, illite, and muscovite. These processes aim to overcome the limitations of individual activation methods while optimizing energy efficiency.

2 Materials and Methodology

Two natural clays from Victoria, Australia (kaolinite-rich K and illite-rich) and a pure kaolinite clay (Ka) from the Clay Mineral Society, USA, were activated via calcination, mechanochemical activation (high-shear grinding), and a combination two methods, i.e., Mechanochemical-calcination (MCC). The clays were dried at 110°C, sieved to 75 μm, and activated based on preliminary studies: calcination at 600°C for 1 hour and mechanochemical activation via planetary ball milling (20 min, 500 rpm, 10:1 ball-to-powder ratio, 10 mm steel balls). MCC involved calcination followed by mechanochemical activation. Activated and raw clays replaced 20% of cement by weight, and cement paste was prepared using a Thinky planetary mixer. Compressive strength, particle size distribution, BET surface area, dehydroxylation (TGA), and amorphous content (XRD) were analyzed. K contained 38% kaolinite, 15% montmorillonite, and 4% illite. Illite-riche had 6% kaolinite and 17% illite and Ka consisted of 96% pure kaolinite.

3 Results and Discussion

3.1 Compressive strength

The compressive strength increase was most pronounced in illite-rich clay (35.8 MPa at 28 days in raw clays). MCC achieved a 58% increase (20.6 MPa), compared to 38% (13.6 MPa) and 41% (14.7 MPa) for calcination and mechanochemical activation. Calcination was most effective for kaolinite-rich clays, with calcined-Ka reaching 82.35 MPa, an 86% increase over raw-Ka (44.2 MPa). Mechanochemical activation and MCC increased Ka-raw strength by 29% and 20%, respectively.

3.2 Physical transformation of clays

As shown in Figure 1(b), calcination increased illite-raw D50 by ~73% due to sintering and agglomeration, while mechanochemical activation reduced it by the same percentage, with an additional ~5% decrease in illite-MCC. K-raw D50 decreased by 27% post-calcination and ~45% after mechanochemical activation, with further reductions at MCC (49%). Mechanochemically activated Ka increased D50 by ~6 times compared to calcined Ka but decreased again with MCC (64% decrease compared to mechanochemical activated).
Specific surface area decreased after calcination for illite-raw (41%), K-raw (16.7%), and Ka-raw (22%). Mechanochemical activation increased it significantly for illite-raw (45%) and Ka-raw (266%) but reduced for K-raw (~50%), with an additional 82% decrease in MCC.

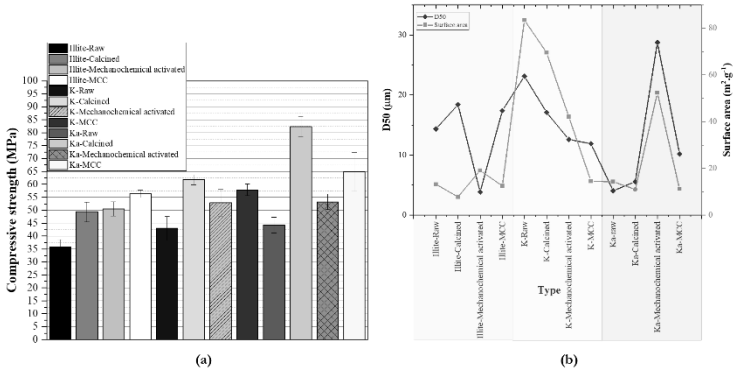

Fig. 1. (a) 28-day compressive strength (b) median particle size (D50) and specific surface area variation with activation.

3.3 Chemical transformation of clays

The XRD spectra revealed that calcination reduced kaolinite peak intensities in all clays, leading to increased amorphous content (Table 1).

Table 1: Amorphous content via XRD

Clay type	Amorphous content (%)
K-Raw	5.1
K-Calcined	33.2
K-Mechanochemical activated	40.4
K-MCC	41.9
Illite-Raw	7.0
Illite-Calcined	19.4
Illite-Mechanochemical activated	21.2
Illite-MCC	25.9
Ka-Raw	32.8
Ka-Calcined	57.9
Ka-Mechanochemical activated	34.8
Ka-MCC	64.7

Clay K showed the highest amorphous content increase with MCC. However, lower surface area led to lower compressive strength in K-MCC and K-mechanochemically activated clays compared to K-calcined, despite higher amorphization. Illite clays exhibited increased amorphous content post-treatment: illite-calcined (12%) and illite-MCC (19%), with illite-MCC achieving the highest compressive strength, independent of surface area and particle size. Ka-MCC had lower compressive strength than calcined Ka clays due to larger particle size, despite slightly higher amorphization.

Degree of dehydroxylation (from TGA) values were 75.1% (K-calcined), 60.2% (K-mechanochemically activated), and 79.1% (K-MCC), correlating with XRD results. Similar values in K-calcined and K-MCC suggest surface area reduction affects compressive strength more than amorphization. Illite clays showed dehydroxylation of 74.4% (illite-calcined), 57.3% (illite-mechanochemically activated), and 81.1% (illite-MCC), explaining illite-MCC's greater strength. Kaolinite clays had dehydroxylation of 91.7% (Ka-calcined),

36.3% (Ka-mechanochemically activated), and 91.1% (Ka-MCC). Strength reduction in Ka-calcined is attributed to increased particle size, as Ka-calcined and Ka-MCC have similar dehydroxylation.

4 Conclusion

This study demonstrates the potential of mechanochemical-calcination as an effective method to enhance the reactivity of Australian natural clays for use as SCMs. The combined activation method significantly increased the amorphous content, degree of dehydroxylation and compressive strength in illite-rich clays, which exhibited a 58% strength improvement compared to raw clays. While calcination alone proved most effective for kaolinite-rich clays, the synergistic effect of mechanochemical-calcination optimized both physical and chemical transformations, achieving superior performance. These findings emphasize tailored activation techniques for utilizing low-grade clays, reducing cement production's environmental impact, and promoting sustainable construction.

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Microwave calcination – a more energy-efficient method of preparing calcined raw materials

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Keywords: calcined clay, microwave, conventional heating, blended cement, pozzolanic activity

Reducing CO_2 emissions in response to global warming remains an urgent global issue, which also affects the cement industry. Traditional Portland cement production is one of the main sources of CO_2 emissions, leading to intense research into alternative materials that can reduce the carbon footprint of the cement industry. One such alternative material is slag, fly ash, and various types of natural or calcined clays, which can serve as a replacement for Portland cement. While clay reserves are quite extensive worldwide, high-quality kaolinitic clay, from which metakaolin is produced, remains relatively expensive. This has led to the search for cheaper, lower-quality clays that, after treatment, can exhibit properties similar to those of Portland cement.

The traditional method of calcining clays involves heating them to high temperatures in kilns, a process that is both time- and energy-intensive. However, alternative heating methods, such as microwave calcination, have shown promise. Compared to conventional heating, microwave heating offers several advantages: faster heating times, more efficient internal heating (as energy is directly supplied via an electromagnetic field), and a reduction in temperature gradients between the material's interior and surface. These advantages may lead to significant energy and time savings, while still achieving a high-quality product suitable for use as a cement replacement. The goal of this study is to compare the products of clay calcination using conventional heating and microwave heating, with the aim of achieving energy and time savings while maintaining or improving the quality of the resulting material.

The raw materials were initially dried and then subjected to quantitative analysis using X-ray diffraction (XRD). For thermal behaviour analysis, differential thermal analysis (DTA) was performed in a dynamic atmosphere, with temperatures ranging from 35°C to 1000°C and a heating rate of 10°C/min. After drying, the raw materials were crushed and sieved, with the 0-10 mm fraction selected for calcination. Calcination was performed using two methods: traditional heating in a muffle furnace and microwave heating in a microwave muffle furnace. Traditional calcination (conventional heating) occurred at a temperature increase of 5°C/min, with the material held at the target temperature for 60 minutes and 20°C/min held at the target temperature for 30 minutes. Microwave calcination was carried out at a heating rate of 20°C/min and hold at the target temperature was 30 minutes. The materials were removed from the furnaces at approximately 200°C. After calcination, the raw materials underwent further analyses, including X-ray diffraction, differential thermal analysis, and color measurement using a handheld spectrophotometer. The pozzolanic activity of the calcined materials was tested using the R3 test, which continuously measures the reaction heat between the pozzolan and excess calcium hydroxide in excess water at 40°C using an isothermal calorimeter. This test is critical for determining the reactivity of the calcined clays, which could serve as cement replacements. After testing the reactivity, selected calcined raw materials were ground, and

blended cements were prepared. Mortar samples were then made with these cements, and their strength characteristics were tested after 2, 7, and 28 days of curing. Some of the polished sections were further examined using optical and electron microscopy.

The results showed that raw materials calcined with microwaves exhibited similar, and sometimes superior, properties compared to those calcined with conventional heating. This suggests that microwave calcination could be a more energy-efficient and time-saving method of producing high-quality pozzolanic materials suitable for use as cement replacements.

This research contributes to the development of more sustainable methods for producing cementitious materials, which can help reduce the environmental impact of cement production. The findings suggest that using cheaper, lower-quality clays instead of expensive kaolinitic clays may provide economic benefits while still being environmentally sustainable. Microwave calcination thus appears to be a promising method for producing high-quality pozzolanic materials that could replace part of Portland cement, leading to a reduced carbon footprint in the construction industry and building materials.

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Mineral Recyclates: An Analysis of Price Perception in Public Construction Administrations

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Keywords: Public Procurement, Mineral Recyclates, Primary Material, Empirical Data.

In 2023, the construction volume in Germany amounted to €558 billion, of which €78.1 billion was allocated to public investments. This underscores the significant market power of public procurement at the federal, state, and municipal levels, along with its substantial capacity to influence market development. As one of the largest clients in the construction sector, public procurement holds the potential to foster market development and provide planning certainty through targeted demand. Nonetheless, public contracting authorities are bound by strict budgetary constraints and must act in accordance with the principles of efficiency. Consequently, all procurement decisions must be based on the criterion of the most economically advantageous tender. In practice, this criterion is generally defined by price, which often results in a preference for potentially cheaper primary raw materials. This practice, however, stands in contrast to the objectives of the Circular Economy Act, which assigns public procurement a model role by requiring authorities to give preference to recycled materials. In doing so, they are expected to accept reasonable additional costs as well as minor impairments in non-essential functional properties.

The research project described focuses on the fundamental decision-making behavior of public contracting authorities, who were surveyed as part of an empirical data collection regarding their barriers, concerns, and willingness to pay for mineral recyclates. The project builds upon the research initiative "*StAR-Bau*" conducted in 2019 by the Karlsruhe Institute of Technology.

This research report presents a focused analysis based on the specific hypothesis: "*The use of recyclates is primarily determined by price.*" The hypothesis aims to explore the personal price perception of employees in public construction administrations. The findings are based on an empirical survey conducted in 2023, the data of which forms the basis for the subsequent analysis.

The hypothesis is grounded in the assumed correlation between the questions: "*How important is the price advantage of recyclates compared to virgin materials to you?*" and "In your opinion, what percentage discount must recycled construction materials offer compared to virgin materials for you to prefer their use?"

The analysis begins with a presentation of the descriptive statistics for the above-mentioned questions. Of the total 44 respondents, 4.5% considered the price advantage unimportant, 45.5% rated it as neutral, and 50.0% deemed it important in order to favor recycled over virgin construction materials. The average expected price advantage among all respondents was 18.7%, with a standard deviation of 13.5%.

To further assess the hypothesis, an additional question was included: "*Would you, within your authority's existing construction budget, be willing to tender potentially more expensive recyclates*?" This question was evaluated in relation to the aforementioned price sensitivity question using a mean comparison approach.

Table 1: Comparison of the Mean Values of the Questions

Willingness to specify higher-cost recycled materials despite a construction budget	Required Percentage Discount	
	Arithmetic Mean	Standard Deviation
Yes, there is a willingness	7.3	5.9
No, there is no willingness	23.3	13.5
Other	14.2	10.7
Total	18.7	13.5

Table 1 visualizes the results in this regard. Interestingly, participants who are generally positively inclined toward the use of recycled materials consider a price reduction of 7.3% to be sufficient. In contrast, participants who fundamentally lack the willingness to use more expensive recycled materials regard a significantly higher average discount of 23.3% as necessary. The comparison of means using Analysis of Variance reveals a statistically significant difference.

Based on the comprehensive evaluation of all survey data, economic policy recommendations have been developed aimed at promoting the stronger integration of mineral recycled materials into the decision-making processes of public construction authorities. To address the aforementioned hypothesis, an alternative approach is examined which seeks to place recycled materials in direct competition with primary construction materials.

As a first step, the key findings from the questionnaire analysis must be consolidated: Descriptive statistical analysis of the hypothesis indicates that 50% of respondents consider price advantage to be a key success factor. Furthermore, the majority of respondents prefer the most economically advantageous offer (36.7%) as the primary award criterion, followed by awarding based solely on price (27.5%). However, a significant inhibiting factor remains: Even among public clients who in principle allow the use of recycled materials in their tenders, construction companies continue to offer only primary materials.

Given the uniqueness of each construction project in terms of material requirements, location, transport distances, and product selection, a more flexible approach should be adopted in the future. As a consequence of the current standard procedure, the implementation of an outcome-open tendering practice is recommended. This involves the parallel pricing of both recycled and primary materials within the framework of base and alternative positions. Targeted market access and equal treatment of certified recycled materials could create economic incentives that support a stable long-term demand for recycled materials independent of government intervention.

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Multi-Criteria Sustainability Assessment for Concrete in Nordic Offshore Wind Applications

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Keywords: offshore wind energy, Low-carbon concrete, Life cycle assessment (LCA)

Introduction

The expansion of offshore wind energy in the Nordic region has been recognized as a critical step toward fulfilling the Renewable Energy Directive EU/2023/2413 of increasing the renewable energy share to at least 42.5% by 2030. Although this expansion contributes to carbon reduction goals, it also introduces concrete technology challenges, due to cold-weather conditions, frequent freeze–thaw cycles, ice loading, and exposure to saline water, all necessitating attention to material durability.
Traditional approaches to concrete sustainability have primarily focused on reducing embodied carbon through the use of low-carbon cementitious materials, such as fly ash and ground granulated blast-furnace slag (GGBS). However, it has been observed that some life cycle assessments (LCAs) do not adequately account for service-life reductions due to, e.g., freeze–thaw deterioration. Such omissions can lead to under- or overestimating actual environmental impacts.
In response to these concerns, a preliminary durability-integrated LCA approach is proposed to support material selection for offshore wind foundations in northern climates.

Methodology

Cradle-to-gate LCA framework
Literature study was conducted to identify concrete mixes incorporating supplementary cementitious materials (SCMs) that meet the XF4 and XS3 exposure requirements specified in the EN 206 standard. For the selected mixes in the database, a cradle-to-gate life cycle assessment (LCA) was performed using SimaPro software and the Ecoinvent database. A boundary was defined from raw material extraction to the exit of the concrete batching plant, including the production, transportation, aggregate processing, and mixing operations. All assumptions were made in accordance with ISO 14044 guidelines. The Global Warming Potential (GWP), measured in kilograms of CO_2-equivalent per cubic meter, was used as the primary indicator. CML-IA baseline V3.10 / World 2000 method was used for the calculation.

Sustainability Index
The durability properties identified in the literature were normalized to a 0–1 scale. These normalized values were then combined into a composite durability index (D) with specific weights based on the durability parameters. A weight sensitivity analysis was conducted to account for the possibility that specific durability attributes might hold greater importance in five scenarios. For each variation, the composite durability index (D) was recalculated. A sustainability index (SI) was introduced to integrate both cradle-to-gate emissions and the composite durability index.

Case study application

The mixes were applied for the case study of the Korsnäs Offshore Wind Farm, located in the Gulf of Bothnia, proposed as a site for large-scale offshore wind farm in Finland. A 22 MW Reference Wind Turbine (RWT) is planned with a gravity-based foundation (GBF) to manage the challenges posed by the region's dense moraine seabed and heavy sea ice loads. The concrete used for these foundations, with a total volume of approximately 2531 m³, contributes significantly to the total project emissions, resulting in interest in lowering the carbon footprint.
For a preliminary calculation, three mixes were selected from the database with corresponding durability parameters, including regular concrete (NC), Ultra-High-Performance Concrete (UHPC), and a concrete mix with 35% cement replacement with natural pozzolan and limestone (SCM). In addition, the Hybrid mix combined a lower-quality 50% SCM-based core with a protective UHPC layer (10% volume), following the promising results from.

Results

Initial LCA calculations indicated that the SCM and Hybrid mixes achieved cradle-to-gate carbon reductions ranging from approximately 30% to 40% relative to a 100% PC reference (NC). On the other hand, as expected, UHPC demonstrated a double GWP compared to REF due to its high PC content of approximately 800 kg/m³. Nevertheless, the combined assessment showed that these relations have changed. When durability parameters were incorporated, the performance differences among UHPC, the reference mix (NC), and the SCM mix narrowed considerably. In contrast, the Hybrid mix consistently maintained a strong overall sustainability score across all scenarios, despite having lower absolute strength. The weight sensitivity analysis further demonstrated that, although ranking positions were generally stable, small changes in weighting factors for freeze–thaw or chloride ingress could alter the order of SI performance. It indicates the importance of accurately identifying local priorities in a given exposure class. According to the analysis, approximately 1329.11 tonnes of CO_2 per foundation can be saved. Extrapolated to a farm with 72 foundations, this amounts to roughly 0.09570 million tons of CO_2 in total savings, translating into an estimated cost savings of about $ 10.34 million.

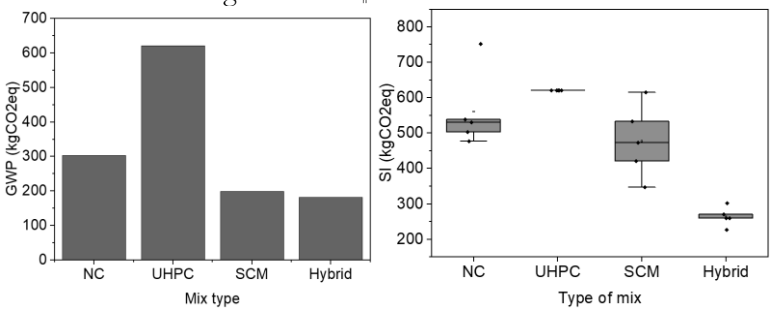

Figure 2 – Results of sustainability assessment. Left: Global warming potential. Right: Sustainability Index.

1. Conclusions

The following conclusions can be drawn from the study:

- Incorporating durability metrics reduces differences among UHPC, REF, and SCM mixes, leading to a more balanced sustainability assessment.
- Optimized designs can save approximately up to 1329 tonnes CO_2 per foundation.
- The composite sustainability index facilitates lifecycle cost reduction and risk management, offering information for contractors, designers, and policy-makers.

Acknowledgement
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Optimizing Sludge Utilization in Construction: A Study on Mechanical, Economic, and Environmental Performance

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Keywords: cement replacement material, mortar, sludge, pozzolanic material

Over the past several decades, managing the large volumes of sludge generated from sewage and wastewater treatment processes has become a significant environmental challenge. Sludge often contains heavy metals and harmful components, making landfill disposal both difficult and environmentally hazardous. Additionally, rising landfill and incineration costs, alongside increasingly stringent environmental regulations, underscore the need for alternative disposal methods. In this context, utilizing sludge as a cement replacement material in construction has gained attention as a potential sustainable solution.

This study evaluates the feasibility of using sludge derived from the wastewater of recycled aggregate washing processes as a cement replacement material. The sludge was collected from a factory producing recycled aggregates from construction waste. Wastewater was filtered to extract suspended sludge, which was subsequently dried to form sludge cakes. A critical issue in such factories is the lack of viable and legal disposal methods for secondary waste generated from construction activities. To address this, the research aims to repurpose sludge as a construction material, targeting at least the minimum structural requirements for concrete blocks or structural members. Economically, this offers the potential to convert waste disposal costs into profits by commercializing sludge-based products.

Previous studies have reported that using raw sludge without pre-treatment often negatively impacts the mechanical properties of mortar and concrete. However, heat treatment can enhance sludge's chemical reactivity, offering promise as a sustainable cement substitute. Therefore, this study adopts two primary approaches: comparing the compressive strength of mortars containing raw versus calcined sludge, and evaluating the effect of supplementary cementitious materials on strength development. Given that sludge from recycled aggregate washing wastewater differs chemically from sludge produced by traditional sewage treatment, the raw material's physicochemical properties were thoroughly examined. The economic and environmental impacts of using sludge as a cement substitute were also analyzed.

Thermogravimetric analysis of the sludge indicated that calcination significantly enhanced its reactivity. Consistent with this finding, the mortar strength with calcined sludge improved at cement replacement ratios of up to 15%, while mortar strength decreased with increasing sludge replacement ratios when raw sludge was used. Despite the performance benefits, the calcination process involves high costs due to electric furnace usage, potentially limiting economic feasibility. To address this limitation, cement was replaced with a combination of raw sludge and pozzolanic materials. This approach resulted in improved mortar strength compared to sludge-only mixtures. Moreover, physical and chemical analyses using X-ray diffraction and thermogravimetric techniques provided insights into changes in microstructure and chemical reactions.

Economic analysis showed that the economic index (strength per unit cost) decreased as the sludge replacement ratio increased, indicating higher costs to meet strength requirements when using sludge alone. Nevertheless, incorporating 20% pozzolanic material led to mortar strength exceeding 75% of that of plain mortar, demonstrating both economic and structural integrity. Environmental analysis further revealed that CO_2 emission reductions increased with higher cement replacement ratios. When evaluating CO_2 reduction relative to strength performance, minimizing cement usage correlated with greater emission reductions. Balancing structural safety, economic feasibility, and environmental conservation, it can be concluded that a mixture with 20% cement replacement by sludge and an additional 20% pozzolanic material emerged as the most efficient approach to meet structural strength requirements while promoting sustainability.

This study demonstrates that sludge derived from recycled aggregate washing wastewater can be a viable cement replacement material, particularly when combined with pozzolanic materials. The findings suggest that this approach can be effectively utilized in the production of construction materials, such as concrete blocks and non-load-bearing structural elements, offering a practical and sustainable solution for waste management in construction industries. Moreover, this research contributes valuable insights for future studies focused on optimizing industrial by-product utilization, promoting circular economy practices, and reducing the carbon footprint of construction materials.

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Parent Concrete Characterization for Selective Demolition: A Case Study of a Dutch Viaduct

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Keywords: Recycled Concrete Aggregate (RCA), Parent Concrete Characterization, AI-Based Segmentation, Selective Demolition, Sustainable Construction Practices

Abstract - The sustainable use of recycled concrete aggregate (RCA) is increasingly vital for addressing environmental challenges and advancing circular construction practices. However, variability in RCA quality, driven by differences in parent concrete properties, poses a significant challenge to its widespread adoption in high-performance applications. This study proposes an AI-driven framework for parent concrete characterization, aiming to predict RCA quality and facilitate selective demolition strategies.

The proposed framework uses advanced AI-based segmentation techniques to evaluate key parent concrete parameters, including water-to-cement (W/C) ratio, cement type, aggregate type, and aggregate gradation. By analyzing high-resolution backscattered electron (BSE) and optical light microscopy micrographs, the framework provides insights into the microstructural and compositional properties of parent concrete. The research focuses on structural members, including prestressed beams, columns and abutment wall, of a viaduct constructed between 1965 and 1970 in the Netherlands.

The analysis revealed significant differences in parent concrete properties across structural members. AI-based characterization techniques proved effective in identifying critical differences in w/c ratio, cement type, aggregate type, and gradation. These insights have paved the way for selective demolition strategies, enabling the recovery of materials optimized for specific recycling processes or construction needs. By effectively reducing material heterogeneity, this research not only advances sustainable construction practices but also maximizes resource efficiency.

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Recycling Construction and Industrial Wastes as SCMs: The Effect of Thermal Treatment and Granulation on SCM Reactivity

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Keywords: Supplementary cementitious materials (SCM), industrial waste recycling, thermal treatment, slag, cement reactivity.

Extensive research is currently being conducted on alternative supplementary cementitious materials (SCMs) that can partially replace clinker, lowering CO_2 emissions and energy consumption to solve the problem of the growing demand for cement, making its manufacturing more sustainable. Due to their accessibility, affordability, and potential pozzolanic or latent hydraulic characteristics, industrial and construction wastes are a viable option. However, the effectiveness of these materials as SCMs is strongly influenced by their mineralogical composition and processing conditions. Mechanical or thermal treatments could be adopted for some materials to enhance their cementitious potential, while others are naturally reactive and the treatment is just a method of enhancing their performance. This study investigates the reactivity of five construction and industrial waste materials that are (1) recycled concrete sand, (2) recycled concrete fines, (3) bottom ash, (4) bed ash, and (5) GCS "a mixture of glass ceramics and stone", under various processing treatment. Each material was evaluated in three states: (i) raw and milled; (ii) thermally treated at 600°C and milled; and (iii) melted, quenched in water to create slags (granulates), and subsequently milled. The main goal was to assess the impact of these treatments on the materials' reactivity, mineralogical phases, and chemical composition when they were utilized as SCMs in cementitious systems.

A systematic approach was employed to assess cementitious potential. Initially, all waste materials were collected, dried, and milled to achieve a comparable particle size distribution. A batch of each material was subjected to heat treatment at 600°C in a controlled furnace environment for one hour, allowing for a potential activation of aluminosilicates. Another batch was subjected to high temperature to reach melting, followed by rapid quenching in water, by doing so, some glassy slag structure could form, which was subsequently milled into a fine powder to enhance its reactivity. The chemical and mineralogical compositions of all processed materials were analyzed using X-ray fluorescence (XRF) to determine the oxide composition and X-ray diffraction (XRD) to identify phase transformations and quantify the crystalline and amorphous content. The reactivity of the materials was further assessed through an activity index (AI) test according to ÖN B3309-1 with CEM I 42.5R, evaluating compressive and flexural strengths at 1, 7, 28, and 90 days, and the R3 test, a rapid screening method to determine their intrinsic pozzolanic or hydraulic potential and to observe the correlation with the AI test.

The results demonstrated that heat treatment and quenching affected reactivity differently depending on the material type. For instance, recycled concrete fines, which primarily contain calcium carbonate and un-

hydrated cementitious phases, exhibited low initial reactivity in the raw state but improved significantly after heat treatment due to partial carbonate decomposition and the exposure of reactive silicate phases. On the other hand, bottom ash, a by-product of waste incineration, showed low strength in the raw state, with heat treatment inducing only slight improvements. However, the quenched slag form of these materials exhibited significantly enhanced pozzolanic properties, as the rapid cooling process led to increased amorphous phase content, which is beneficial for cement hydration reactions.

Among the investigated materials, the granulated recycled concrete sand showed the highest performance as SCM, showing an activity index (AI) value of 1.01 after 7 days of curing. The melting and quenching process helps develop an amorphous phase that significantly contributes to long-term strength development as it is much more reactive than crystalline phases. The activity index test results confirmed that while some heat-treated materials exhibited improved early-stage reactivity, quenched slags demonstrated superior long-term performance, making them strong candidates for sustainable cement applications. Furthermore, XRD analysis showed that heat treatment at 600°C helped in the activation of certain phases while quenching led to the formation of a disordered glassy structure, which enhanced the materials' pozzolanic and latent hydraulic reactivity as it was aforementioned.

This research demonstrates that industrial and construction wastes can be successfully transformed into high-performance SCMs through controlled thermal treatment and granulation processes. The results provide valuable insights into these materials' reactivity, phase transformations, and performance, paving the way for their large-scale implementation in cement production. Future work will focus on evaluating the mechanical performance, durability, and microstructural evolution of these materials in cement and concrete applications, as well as conducting a leaching test to ensure assessing the environmental safety and feasibility for large-scale implementation.

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Recycling of electro-dialytically treated wood fly ash as a partial substitution for clay in bricks

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Keywords: Wood fly ash, recycling, circularity, clay brick, electrodialytic treatment

Introduction

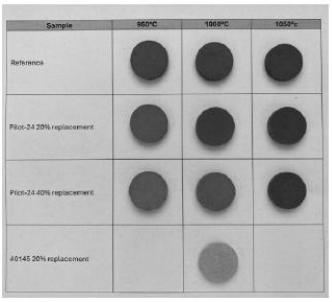
Clay for brick production is a finite resource, and finding secondary raw materials for partially substituting clay in bricks gains increased interest. The material must not compromise the quality of the bricks produced or the environment. In the last decades, an increase in the use of wood in heating and power production has been seen, resulting in vast amounts of wood ashes. These can be spread on agricultural land or in forests, but the regulations are strict in relation to, e.g., Cd and conductivity, leading to a limit per hectare, which is so low that it is rarely economically feasible. The wood fly ashes (WFAs) generally contain a higher Cd concentration and have higher conductivity than the wood bottom ashes. WFA is generally handled as waste today as its characteristics do usually not support recycling. This work deals with the utilization of electro-dialytically (ED) upgraded WFA in bricks to investigate if such treatment can enhance the characteristics.

Materials and methods

A WFA from circulating fluidized bed incineration of wood chips at 760-930 °C was treated by ED in the tube reactor described in [1]. The WFA before and after treatment was characterized and compared to the characteristics of the brickwork clay of the investigation (clay for red bricks). Here the concentrations of macro elements and Cd measured according to the US EPA 3015A method are compared. Small brick specimens with 0, 20, or 40% clay replacement with ED-treated WFA were fired at 950, 1000, or 1050 °C, and for comparison, 20% untreated WFA at 1000 °C.

Results and discussion

	Clay	WFA	ED-WFA
Al (g/kg)	11.3	17.3	8.3
Ca (g/kg)	7.6	179	8.4
Cd (mg/kg)	0.7	11.1	2.2
K (g/kg)	1.7	20.1	10.0
Mg (g/kg)	2.5	19.3	4.7
P (g/kg)	0.2	13.6	3.3



From Table 1, it is seen that the concentration of all the reported elements is much higher in the WFA than in the clay, while after ED upgrading, the concentrations are generally much closer to the clay concentrations.

The differences in the brick specimens can be seen, e.g., from the colors of the 20% replacement, which is pale yellow for the WFA, while brownish with ED-WFA.

Table 1: Concentrations in clay, WFA, and ED-WFA Figure 1: The fired brick specimens

The pale color is most likely due to the high content of Ca in the WFA, and it reveals that different sintering products are found.

Conclusion

This work shows that an upgrading of WFA characteristics for use as a partial replacement of clay in bricks can be obtained by an electro-dialytic treatment.

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Recycling of Wind Turbine Blades Fibers into PVC Roofing Membranes

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Keywords: Recycling, waste wind turbine blades, secondary polymer composites, poly(vinyl chloride)

The human dependence on wind energy will increase in the upcoming years to reduce environmental impacts coming from the energy sector. Unfortunately, due to the limited lifetime of wind turbine composite blades and challenges regarding their recycling, an already massive and rapidly increasing amount of composite waste is produced. Secondary utilization of this waste can offer a solution. Incorporation of wind turbine blade waste into PVC roofing membranes can prevent problems including shrinkage and limited fracture resistance during installation, offers a more sustainable alternative by reducing the amount of virgin PVC, and has the potential to reduce the costs. Therefore, this thesis aims to produce cost-effective and high-performance PVC roofing membranes utilizing mechanically recycled wind turbine blade waste, making them competitive with commercially available PVC roofing membranes. The research question is formulated as: How can wind turbine blade waste be effectively implemented into PVC roofing membranes to create a more sustainable option compared to commercially available PVC roofing membranes? The research is composed of three phases: the development of a method to treat waste glass fibers, followed by the development of a procedure to produce composite membranes, and finally, the analysis of the fabricated composite membranes. Compression molded composites revealed that the addition of 5 wt% maleic anhydride-grafted-PVC enhances the tensile strength, tensile modulus, and fiber-matrix interactions, indicating that compatibilizer was the most effective. Using this compatibilizer, composite membranes were successfully produced following a three-step procedure: 1) pre-mixing, 2) compounding via twin-screw extrusion, and 3) flat die single-screw extrusion followed by mini-calendaring. The composite membranes exhibited reduced high-stress properties including tensile strength, average tear growth force, and puncture force, whereas low-stress properties, including tensile modulus and water vapor permeability were improved in comparison with pure PVC. This can be attributed to insufficient actual fiber lengths that did not exceed the critical fiber length. To overcome this limitation, future research is needed. Research into the production of waste wind turbine blade – PVC composite roofing membranes following the industrial lamination procedure and additional testing would be beneficial.

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Reducing Clinker Dependence: The Economic Potential of Ternary Cement in Fiji

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Abstract

To address the issue of global warming, a great emphasis has been made on reducing the carbon footprint of the cement industry. Substitution of clinker with supplementary cementitious material can significantly address this issue. This work analyses the costs associated with cement production in Fiji (clinker importing nation), cement mixes are created by blending locally sourced supplementary cementitious materials (SCMs) with ordinary Portland cement (OPC) at substitution levels of 15%, 35%, 50%, and 65% of the clinker with SCMs. The supplementary cementitious materials (SCMs) include Natural Pozzolan (NP), Limestone, and Calcined Clays (CC). The cost comparison includes the total expenses related to the production of each cement type by a cement producer, Pacific Cement, in Fiji. This includes the costs of material extraction within Fiji, transportation from the mining site to the cement facility, and the grinding and blending of these materials with cement clinker. The cost of cement is determined by evaluating the output of one tonne of cement.

Keywords: Natural Pozzolan, Calcined Clays, Cost of production, Fiji

The cost of various raw materials includes the cost of mining and transportation of raw materials to the Pacific Cement facilities located at Suva, Fiji. The cost of transportation is assumed as 0.15 USD/km/tonne, The cost of grinding raw materials is taken as 9 USD/tonne, the cost of packing is taken as 15 USD/tonne, and the cost of labour is taken as 2 USD/tonne. The type of calciner assumed is a rotary kiln, whose calcination cost is 15 USD/tonne, and the cost of grinding, packing, and labour are assumed as they are currently in Fiji. Clinker and gypsum are imported in Fiji, so the cost of clinker includes the cost associated with shipping clinker to the cement plant of Pacific Cement at suva, Fiji. Natural pozzolan, clays, and limestone are available in Fiji. In the case of clays, the calcination cost of clays using a rotary kiln is included, and it is the additional cost apart from mining and transporting cement.

The Portland pozzolan cement made by replacing natural pozzolan was more economical than LC^3 at 15% replacement of clinker, because the replacement of clinker in LC^3 is possible at the replacement of 50% and 65% LC^3, LC^3 is found to be more economical and practical in the conditions of Fiji. LC^3 -35 has the highest cost-to-strength ratio.

With the manufacturing of LC^3, Fiji will be able to use its local resources to manufacture cement and reduce its dependency on imported clinker, which will not only save the cost of import but also earn foreign exchange by exporting the LC^3 to other Pacific Small Island and Developing States. With the use of LC^3 in Fiji, the cost of cement for the end user is reduced, which will result in the construction of affordable houses that are disaster-resilient and affordable.

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Semi-empirical prediction of mechanical properties of recycled aggregate concrete

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Keywords: concrete, recycled aggregates, compressive strength, elastic modulus, predictive approaches.

Introduction

Due to the decreasing availability of natural aggregates, using recycled concrete aggregates (RCA) obtained from demolition presents a significant opportunity to preserve natural resources and to promote a circular economy. Currently, RCA are mostly used in larger sizes (>16 mm) and at quite moderate substitution levels (still limited to 20% in many countries). Fine RCA (< 16 mm) and high replacement levels strongly affect fresh and hardened concrete properties, often requiring concrete mix adjustments. While semi-empirical expressions exist to predict compressive strength and elastic modulus for conventional concrete, the lack of such approaches for recycled concrete (RC) limits its widespread use. The aim of this project is to improve the prediction of these mechanical properties by adapting existing, practice-oriented, semi-empirical equations for fine RCA and high substitution levels.

Applied methodology

32 concrete mixes incorporating RCA with replacement levels from 25% to 95% were manufactured and tested for compressive strength and elastic modulus at 28 days, serving as initial input for modifying existing expressions to predict compressive strength and elastic modulus based on the concrete recipe only.
For predicting the compressive strength, a widely used expression proposed by Bolomey serves as the basis while introducing additional coefficients reflecting the replacement proportion of natural aggregates by RCA and the quality of recycled aggregates. These coefficients are calibrated using the obtained experimental data.
The elastic modulus equation from the Swiss concrete structures code (SIA 262), correlating the elastic modulus to the compressive strength, is adapted by adding factors for the quality and replacement fraction of RCA. In addition, physical mixture models are used for the prediction of the elastic modulus considering the concrete as a combination of the properties of the cementitious matrix and the aggregates and their respective volume fractions. Recycled concrete aggregates, however, are a two-phase material comprising the virgin natural aggregate and the old cement paste adhering to it. The adhered cement paste content was determined by calculation, as experimental measurements are not very reliable, presuming that the measured water absorption and density of RCA result from a combination of the typical water absorption and density of natural aggregate and of the cement paste. The assumed volume fraction of adhered cement paste is determined by minimizing the error in the calculated water absorption and density of RCA. The adhered cement paste is added to the new cement volume in RC. The elastic modulus of the cement matrix was measured in lab tests, and the elastic modulus of the natural aggregate is obtained by reverse engineering.

Obtained results

The compressive strength predictions show good precision and reliability, with a ratio of experimental to estimated value of 0.998 on average and a coefficient of variation of 7.9%. These results are currently based on own data only but will be expanded with comparisons to external data for the full paper. If space allows, we also intend to include a comparison with predictions by machine learning.

For elastic modulus predictions, applying the modified SIA 262 equation to our experimental data shows an average ratio (exp/pred) of 0.99 and a coefficient of variation of 5.7%. Applied to more than 200 external data points, covering a large range of water/cement ratios, an average ratio (exp/pred) of 1.00 and a coefficient of variation of 6.3% are obtained. Applying mixture laws yields even better results with an average ratio (exp/pred) of 1.00 and a coefficient of variation of 4.7%, offering a more detailed prediction by accounting for the specificities of RCA but requiring considerably more detailed information.

Conclusion

The proposed semi-empirical expressions provide reliable predictions for the compressive strength and elastic modulus of RC, even at high substitution levels and with fine RCA. The modifications of Bolomey's expression and the SIA 262 elastic modulus formula improve accuracy while maintaining a practical, user-friendly approach. By offering improved predictive capabilities, this study contributes to the broader adoption of RCA in concrete production, thereby supporting sustainable construction practices. Future research could further refine these models by calibrating and categorizing the coefficient values based on their typical characteristics, such as water absorption and density.

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Separation of Recycled Concrete Fines – Improving Processing Efficiency

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The reuse of mineral fractions from construction and demolition waste (CDW) is vital for a sustainable and circular built environment. While coarse aggregates are already commonly reused in new concrete, the fine fraction—recycled concrete fines (RCFs) below 125 μm—remains largely untapped. This is due to its complex composition, source-dependent variability, and limited understanding of its performance in cementitious applications.

Recent studies suggest that finer RCFs are enriched in cement paste residues and calcium-bearing phases, which may contribute to hydration and binding capacity. However, existing separation methods struggle to produce sufficiently uniform fine fractions. To address this gap, this study explores air jet sieving as a dry classification technique to improve the quality and processability of RCFs for potential high-value reuse.

Two fine-grained materials will be investigated: (1) Industrial RCFs dry sieved below 63 μm, and (2) Ultrafine concrete dust collected from the filter unit of an industrial recycling facility. Both materials originate from concrete pre-crushed with an industrial modified jaw crusher a technology that selectively liberates cement paste from aggregates at early processing stages. Each sample will undergo secondary separation with an air jet sieve targeting the <40 μm fraction. This study aims to assess how this step affects particle size distribution, composition, and reactivity.

The materials properties will be characterized through laser particle size distribution analysis, X-ray fluorescence (XRF), and X-ray diffraction (XRD), thermogravimetric analysis (TGA), and reactivity will be evaluated by isothermal calorimetry. Special attention will be given to the cementitious potential of the dust fraction, hypothesized to contain elevated levels of reactive calcium phases.

By evaluating air jet sieving as a scalable, dry processing step, this study contributes to the development of tailored separation strategies for recycled fines. The findings aim to support their integration into circular material cycles and improve the value retention of CDW streams.

Keywords: recycled concrete fines, air jet sieve, material characterization, concrete dust, circular construction.

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Short-term compressive creep of recycled aggregate limestone calcined clay cement concrete

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Key words: Limestone calcined clay cement, recycled fine aggregate, compressive creep, shrinkage, creep compliance, compressive strength.

Abstract: Reducing clinker content in cement by using supplementary cementitious materials has become widespread due to their performance, economic, and environmental benefits. Although a few studies have been reported on the basic creep of limestone calcined clay cement (LC^3) pastes and mortars, there is a notable lack of literature at the concrete level. This study aims to investigate the short-term compressive creep behaviour of LC^3 concrete utilising 100% recycled fine aggregates (RFA) derived from construction and demolition waste. Three concrete mixes were prepared: a control mix (without limestone calcined clay), an LC^3 mix, and a mix with 100% RFA. Cylindrical specimens, measuring ϕ100mm × 200mm, were prepared with a water-to-binder (w/b) ratio of 0.55. The creep response under sustained compressive load at 30% of the 28-day cylinder compressive strength was measured through compressive creep tests for all mixes. Additionally, three specimens per mix were tested for shrinkage throughout the creep test duration. The LC^3 concrete specimens exhibit drying shrinkage strains that are 13% lower than the control mix at 28 days. The addition of 100% RFA to the LC^3 concrete results in drying shrinkage strains that are 2% lower than those of LC^3 concrete. Compared to PC concrete, the 100% RFA-LC^3 specimens have drying shrinkage strains 15% lower at 28 days. Furthermore, LC^3 concrete exhibits 3% lower creep strains at 28 days compared to PC concrete, while the 100% RFA-LC^3 concrete specimens exhibit 18% lower creep strains compared to LC^3 concrete. Moreover, 100% RFA-LC^3 concrete reveals 20% lower creep strains than PC concrete. The creep compliance of LC^3 concrete is lower than that of PC concrete, while 100% RFA-LC^3 concrete specimens present the lowest creep compliance. LC^3 concrete exhibits a lower creep compliance compared to PC concrete, due to the presence of LC^2, which promotes the formation of a highly densified C-S-H structure. The densified C-S-H structure enhances the stability of the concrete matrix, reducing porosity, and lowering creep compliance. Moreover, due to the pozzolanic reactions, the hydration products of the LC^3 concrete are more diverse than those of PC concrete. The reactions consume Portlandite, Aluminum-Silicate, limestone, and water to produce calcium alumino silicate hydrate (C-A-S-H) and AFm phases (alumina, ferric oxide, and monosubstituted phases). Furthermore, the RFA contains significant quantities of CaO and Al_2O_3, which participate in supplementary pozzolanic and hydration reactions. These supplementary reactions contribute to the formation of additional hydration products, such as carboaluminates, which further densify the concrete matrix, thus reducing the creep compliance. Conclusively, the use of RFA in LC^3 concrete formulations presents a sustainable and innovative approach in the design of durable concrete structures, as evidenced by the lower creep compliance.

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Sustainable management of spent sulfuric acid: gypsum recovery and its application in cement production: a case study of NOAH, Norway

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Keywords: Spent sulfuric acid; Gypsum; Cement production; Life cycle Assessment

In 2022, global sulfuric acid production reached approximately 265 million metric tons, with projections estimating an increase to 321 million metric tons by 2030. Due to its extensive use in various industrial processes, spent sulfuric acid requires proper treatment or recycling to mitigate its environmental impact. The two primary approaches for managing spent sulfuric acid are regeneration for reuse and neutralization. High-concentration spent sulfuric acid is generally more suitable for regeneration, whereas low-concentration acid containing various contaminants is typically neutralized.

Neutralization of spent sulfuric acid is commonly achieved using alkaline additives such as caustic soda, liquid ammonia, quicklime, limestone and slaked lime. Several industrial by-products have also been explored as alternative calcium sources, including coagulation sediments from surface water treatment, alkali residues from paper mills and cement kiln dust. These materials have proven effective in neutralizing spent sulfuric acid; however, their availability is often constrained by regional distribution and supply limitations.

At NOAH, approximately 200,000 tonnes of 25% spent sulfuric acid are treated annually through safe disposal and reclamation practices. The acid is neutralized primarily with alkaline air-pollution control residue (APCR) from municipal solid waste incinerators. The resulting gypsum matrix has proven to be effective in stabilizing heavy metals and other hazardous components while being used in the rehabilitation of a decommissioned limestone quarry outside of Oslo, Norway. But as landfill capacities are diminishing, waste handlers, such as NOAH, are working on adapting to a more circular future by developing alternative treatment and recovery processes. However, due to challenging and highly variable physical and chemical properties, recovery of resource from waste fractions have proven to be notoriously difficult. Any recovery process will not only have to be economically sustainable but will also have to be of a certain robustness to handle the large variation in waste properties. Thorough characterization of the wastes and its products will therefore be essential to support their use in high-value applications.

Natural gypsum plays a crucial role in cement manufacturing by regulating cement setting behaviour. As such, any alternative gypsum source must be rigorously evaluated for its suitability. This study investigates the properties of gypsum derived from various waste streams and assess its feasibility for use in cement production, with a particular focus on technical performance, economic viability, and environmental sustainability.

The methodology employed in this research includes a comprehensive characterization of gypsum products obtained from various treatment processes and waste streams, the preparation and evaluation of cement incorporating these gypsum products, and a life cycle assessment of the resulting cement production. The

performance of the prepared cement was evaluated in accordance with EN196 and EN197. A commercial gypsum sample was used as a reference, while the clinker was supplied by Heidelberg Materials.

The chemical composition of the generated gypsum is highly dependent on the chemical properties of the sulfate and calcium sources used in its production. When used in cement production at a gypsum-to-clinker ratio of 5:95, these gypsum fractions produce cement with desirable setting behaviour, soundness, sulfate content, insoluble residue content, and loss on ignition. The 28-day compressive strength is slightly lower than that of cement made with pure gypsum, likely due to the impurities introduced by the gypsum products. Any chlorides should be minimized through an additional washing process. However, using these gypsum products in cement manufacturing still offers significant cost and CO_2 emission reductions. This highlights a sustainable approach to recycling both spent sulfuric acid and lime-containing byproducts.

This study demonstrates a promising solution for utilizing gypsum recovered from waste streams as an alternative additive in cement. The findings emphasize the potential of locally available industrial residues in Norway, providing a theoretical foundation for regionally adapted recycled gypsum production and contributing to a more sustainable and resource-efficient industry.

Acknowledgement
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Sustainable Materials from Antiquity: Lime Mortars in Teos Ancient City in İzmir, Türkiye

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Keywords: heritage material, ancient lime mortar, mortar characterization, pozzolanic aggregate

The historical lime mortars reflect the engineering knowledge and skills of the antiquity, particularly through their ability to bond rubble masonry and enable the construction of vaulted structures. Prior to the invention of modern concrete, this material enabled construction of monuments that have endured to the present day. One of the most significant properties of this mortar was the employment of pozzolans in its mixture. Pozzolans, which were of volcanic origin or fired ceramic materials such as bricks and tiles, gave mortars the hydraulic ability to set in the presence of water and increased mechanical strength. Investigation of the historical lime mortar characteristics is crucial to understand the production technologies and material compositions. The aim of this study is to determine the characteristics of Roman lime mortars from various buildings of the ancient city of Teos, which was an ancient harbour city located in Sığacık, İzmir, Türkiye. The results will provide a scientific basis for the sustainable conservation of the original building materials.

In this study, eight mortar and plaster samples dated back to the Roman Period (c. 1st and 2nd century AD) were investigated. Samples were collected from the bouleuterion (council house), theatre, cistern, nymphaeum (monumental fountain), harbour pier and heroon (shrine) (Fig. 1). Five samples were taken from structural parts of the buildings, such as the rubble cores of walls, foundations, and vaults. One sample was a wall finishing plaster. Two samples were adhesives used for marble wall and floor coverings. Mortar used for the adhesive of the marble floor covering consisted only of brick aggregates, while other mortar and plaster samples were consisted of both brick and natural aggregates.

The characteristics of the lime mortars were defined by basic physical properties, raw material compositions, hydraulic properties, pozzolanic properties, mineralogical and chemical compositions. Basic physical properties of mortars and plaster were measured according to the RILEM Standard Test Methods. To determine the raw material compositions, samples were rested in dilute hydrochloric acid solution (%5) until the calcite content was completely dissolved and lime/aggregate ratios were measured accordingly to the related weight loss. The hydraulic characteristics of binders (fine mortar matrices, <53µm) which are free from large, grained aggregates were determined through thermogravimetric analysis (TGA). The weight losses associated with the release of chemically bound water (H_2O) between 200–600 °C and the decomposition of carbonated lime, which releases CO_2 between 600–900 °C were evaluated. The binders were classified as hydraulic when the CO_2/H_2O ratio was found to be less than 10. The mineralogical compositions of the binders and fine aggregates (<53µm) were determined using X-ray diffraction (XRD), while their chemical compositions were analysed through scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS). Pozzolanic activity of the aggregates was identified by electrical

conductivity difference between saturated calcium hydroxide solution before and after the addition of fine aggregates. If the differences were greater than 1.2 mS/cm, the aggregates possessed pozzolanic properties.

The density of the samples varied between 1.34 and 1.93 g/cm3 and the total porosity between 21.06% and 44.46%. Lime/aggregate ratio of the samples were in between 1/3 and 1/1. Basic physical properties and raw material compositions were found to be similar and did not change according to their architectural use. The binders were all comprised of calcite, quartz, muscovite, and alkali feldspar minerals. The binder of the mortars in the rubble masonry infill of the harbour pier and heroon exhibited halite mineral and small amounts of Na_2O (1.75% and 5.71%) and Cl_2O (1.13% and 5.55%) in SEM-EDS, likely due to their interaction with sea water. In general, binders were mainly composed of high amounts of CaO (23.24%–50.96%) and SiO2 (34.73%–49.94%), as well as moderate amounts of Al_2O_3 (10.66%–20.54%). The CO_2/H_2O ratios ranged between 1.63 and 9.92, indicating that all samples can be classified as hydraulic.

The aggregates were all comprised of quartz, muscovite, and alkali feldspar minerals. Electrical conductivity differences confirmed all aggregates possessed pozzolanic properties, with electrical conductivity difference values between 4.01 and 7.17 mS/cm. Additionally, SEM-EDS results of aggregates revealed similarities in all samples. SiO_2 amount was the highest (63.34%–79.14%) with moderate amounts of Al_2O_3 (10.38%–18.97%) and Fe_2O_3 (6.15%–7.68%).

The characteristics of lime mortars and plaster of Teos did not vary accordingly to their architectural use. Lime mortars and plasters were hydraulic due to the use of pozzolanic aggregates. No significant differences were observed regarding the mineralogical and chemical composition of the binders. However, exposure to salty water resulted in the formation of halite. The use of brick aggregates in combination with natural ones may suggest the efficient use of available material sources in the city. Conservation efforts at Teos should be compatible with original mortar characteristics to achieve sustainable conservation.

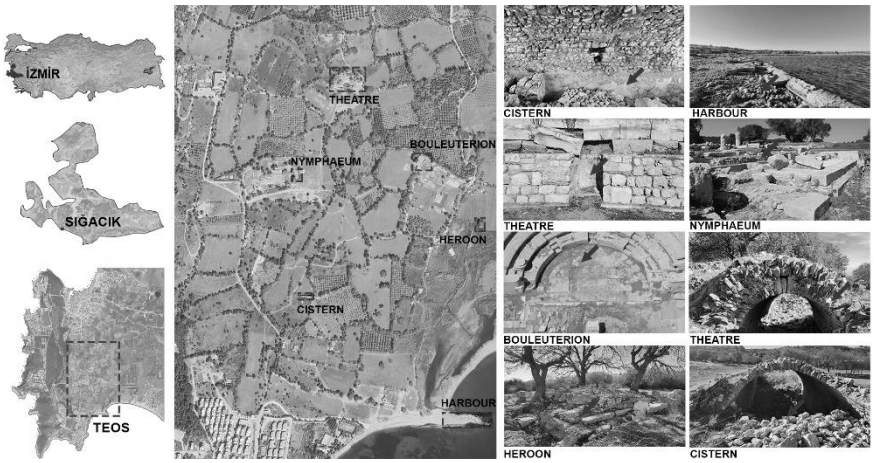

Fig. 1: Sampling Locations of Mortar and Plaster Samples in Ancient City of Teos, Sığacık, İzmir, Türkiye

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The impact of recycled concrete fines quality on the burnability and reactive phase content of carbonatable clinkers

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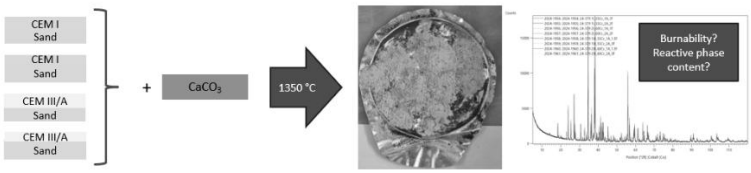
Keywords: Carbonatable clinker, belitic clinker, recycled concrete fines, mineral carbonation

Mineral carbonation can combine CO_2 storage with the production of construction materials. Especially when starting from calcium silicate feedstocks, such as steel slags, the reactivity of the materials lends itself well to an economic and CO_2-negative production flowsheet. The current demand for construction materials is an order of magnitude higher than the supply of suitable feed materials. The production of clinkers is deeply embedded in the cement and concrete sector as solution to such problem. Therefore, an interesting pathway is to produce carbonatable clinkers that are optimized to react with CO_2. These clinkers target a phase assemblage rich in calcium silicates with a lower Ca/Si ratio than C_3S. The C_2S polymorphs are most widely studied, although also rankinite (C_3S_2) and wollastonite have been previously identified to be favourable precursors for mineral carbonation. Clinkers are usually made from virgin materials, but to increase the circularity of the clinkering process and partially replace limestone to reach the required Ca-content, the use of recycled concrete fines (RCF) has been the topic of research and development. The RCF can originate from crushing different types of concrete and crushing plants each have their own effectivity of liberating the paste from the sand. The cement type and cement/sand ratio will thus differ as a function of time and place, the effect of which needs to be known to enable a stable clinkering process.

This contribution provides insights from a systematic study that used synthesized RCF with varying cement/sand ratio (1:1 and 1:2) and cement type (CEM I and CEM III/A). These RCFs were crushed and mixed with $CaCO_3$ to produce carbonatable C_2S-rich clinkers at 1350 °C. The phase composition was measured using X-ray diffraction (including Rietveld refinement and amorphous content quantification using an external standard).



The results showed minor differences between the clinker phase assemblages. An increased proportion of sand in the RCF only raised the required $CaCO_3$ content with approximately 5 wt%, for example from 55 wt% in the raw meal to 60 wt% to reach a similar phase composition. The switch from CEM I to CEM III/A involves only a slight decrease of the Ca/Si ratio and therefore only a minor impact on the phase assemblage. The most noticeable difference was the presence of a minor amount of bredigite due to the presence of Mg in the blast furnace slag.

These results show the robustness of the production of carbonatable clinkers towards RCF input quality. A variation in cement type will not provide a large impact on the quality of the clinker. The liberation of the cement paste (the cement/sand ratio) is important to know of the input material and can be compensated with a raw meal adjustment of an order of magnitude of 5 wt% $CaCO_3$ in the worst-case scenario, but a slightly worse liberation does not endanger the integrity of the process. The performance of the carbonatable clinker might be further safeguarded by the lower dependence of reactivity on the quantitative phase assemblage in comparison with Portland cements. More specifically, varying the C_3S to

C_2S ratio in Portland clinker will endanger substantially the hydration kinetics, while varying the ratio between C_2S and rankinite will have minor impact on the carbonation reactivity. Although for the latter a quantitative relation still needs to be found, this is positive for the implementation potential of carbonatable clinkers from sources with variable input materials, such as RCF.

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The performance enhancement of carbon capture of C-S-H through tailoring the multistep nucleation pathway

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Keywords: C-S-H, non-classical nucleation, calcium carbonate, carbon capture

The rapid increase in atmospheric CO_2 concentration has been persisting for several decades of years, rising by approximately 30 ppm in the past 15 years, thereby exacerbating environmental and climatic challenges. This underscores the importance of carbon capture and storage (CCS), widely regarded as the key strategy to mitigate CO_2 emission. Historically, CCS has been implemented through post-combustion capture at the major CO_2 sources, effectively retarding the emission However, this approach does not directly remove CO_2 from the atmosphere, making it insufficient to achieve a net reduction in atmospheric CO_2 levels. Thus, direct air capture (DAC) has emerged as a focal point of research. The selection of adsorbents for DAC is highly demanding due to the extremely low partial pressure of CO_2 in the atmosphere. Fortunately, the strong CO_2 affinity of calcium silicate hydrate (C-S-H) presents a promising solution. C-S-H serves as the dominant product in Portland cement hydration, accounting for over 60% by volume in hardened Portland cement paste. Developing the carbon capture capacity of C-S-H can partially offset the carbon footprint of the cement industry. Recent studies have demonstrated that C-S-H can react with CO_2 in air, generating calcium carbonate and amorphous silica gel. However, the slow kinetics restricts the performance of C-S-H as the DAC adsorbent. The C-S-H features a relatively high specific surface area (SSA) of about 100 m^2/g, benefited from the foil-like morphology. Nevertheless, the majority of the foil surfaces overlap due to aggregation during formation, limiting the ability of C-S-H to interact with and capture the sparse CO_2 in the atmosphere. To address this problem, a novel approach of preparing C-S-H was inspired by the multistep nucleation of C-S-H. Specifically, after the dissolution of calcium and silicate ions, C-S-H undergoes an intermediate metastable precursor stage, during which the precursor is isolated and dried. This precursor possesses a homogeneous elemental distribution in the matrix, a globular morphology with a disordered atomic structure, and importantly, retains the ability to transform into the foil-like C-S-H in aqueous environment. C-S-H forms when the precursor is placed in pure water. The transformation would finish within 24 h after the immersion. Finally, C-S-H foils with minimal overlap were synthesized through transformation on the solid framework provided by the precursor. Nothing changed including the chemical composition or the structure of silicate chain, but the microscopic morphology. Consequently, the SSA of such C-S-H solid can reach up to 500 m^2/g, four times higher than the conventional C-S-H. The kinetics of atmospheric CO_2 adsorption is also enhanced from 10 mg/g to 40 mg/g within 1 h. Notably, both types of C-S-H present a similar maximal capacity of ~150 mg/g through an accelerated carbonation despite the SSA is elevated, because of the unchanged chemical composition. Moreover, the carbonation product of this C-S-H transforms into vaterite, whereas conventional C-S-H predominantly forms aragonite, which is attributed from its lower pore size. This study not only highlights the potential of multistep nucleation in controlling the properties and enhancing the performance of C-S-H, but also provides a pathway to improve its direct air carbon capture efficiency, suggesting a possible enhancement in the carbon capture capability of cement-based materials.

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Thermo-mechanical treatment of construction and demolition waste recycling sludge for use as supplementary cementitious material

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Keywords: Supplementary cementitious material, Construction and demolition waste, thermal activation, mechanical activation, lime reactivity

Recycling construction and demolition (C&D) waste into valuable products offers a sustainable solution for the construction industry and waste management. Normally, this waste is processed into coarse and fine aggregates using either dry processing or wet processing. In wet processing, high-pressure washing systems are used to remove fines and impurities from the surface of aggregates. The resulting wash water is then treated with thickening agents to allow agglomeration and settlement of the fines. The settled fines are then treated using a filter press to remove the excess water from the fine powder sludge. The resulting sludge contains fine particles from processed materials such as aggregates, concrete, bricks and tiles, which can be dried to produce fine powder and then activated to be used as a supplementary cementitious material (SCM). Over the past decades, numerous studies have been conducted to explore the potential of using recycled fine powder from concrete waste. However, there are limited studies on the utilization of mixed recycled powder such as the one used in this study, which is derived from a combination of various C&D materials in a commercial C&D recycling facility.

In this study, a thermomechanical treatment route was adopted to activate sludge collected from a C&D waste recycling plant located at Hyderabad, India. At the plant, materials such as glass, wood, steel and plastics are first separated from the mix C&D waste. The remaining waste, which includes concrete, mortar, bricks, tiles, ceramics, etc., is processed into coarse and fine aggregates in a wet processing system, similar to the setup commonly found in many such facilities across India. Therefore, the sludge collected from the plant is expected to be a mixture of fine particles of aggregates, sand, hydrated cement, bricks, tiles, ceramic and similar materials. The collected sludge was first dried at 105 ^{O}C to remove excess water and then ground various degrees of fineness (designated as F1 and F2) using a laboratory ball mill. The ground dried sludge powder (F1) was considered as reference and was used to study the influence of thermal activation. Activation temperatures of 500°C and 800°C were selected based on thermogravimetric analysis (TGA). The influence of activation methods on the physical properties such as specific gravity, particle size distribution, surface area and morphology were investigated, along with changes in chemical composition using XRD and TGA. The reactivity of the reference sludge (named F1) and activated sludges (named F2, T500 and T800) was measured using modified lime reactivity (MLR) test. The MLR strength of the activated sludges was compared with a commercially available fly ash to understand the potential of sludge with commonly used SCM. The MLR test results, shown in **Figure 12**, indicate that the mechanical activation through grinding marginally improves the pozzolanic reactivity of sludge, whereas the thermal activation led to a significant enhancement in the reactivity. Interestingly, increasing the activation temperature from 500 ^{O}C to 800 ^{O}C doesn't show additional benefit in the reactivity. Moreover, the thermally activated sludges have reactivity comparable to that of the commercially available fly ash. This indicates significant potential of utilizing C&D waste as SCM for partial replacement of cement in concrete.

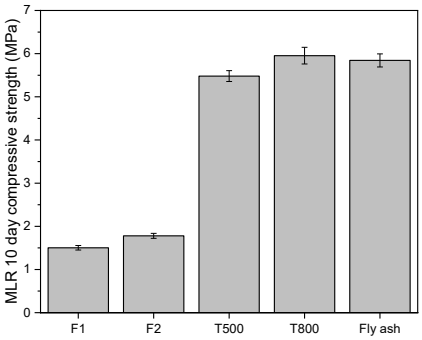

Figure 12 10-day compressive strength of mortars based on modified lime reactivity test

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Treatment of Recycled Concrete Aggregates with Recycled Concrete Powder Slurry

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Keywords: Recycled concrete aggregate; treatment; impregnation; pozzolan slurry; recycled concrete powder

Sustainability has been a major concern in the construction industry over the last decade, with increasing efforts to enhance the environmental performance of concrete. One of the most promising approaches is the utilization of recycled concrete aggregates (RCA) in concrete production. To date, construction and demolition waste has predominantly been used in downcycling applications, such as road subbase or filler material. However, research has increasingly focused on upgrading these applications toward concrete production, a more sustainable upcycling approach. For RCA to serve as a viable alternative to natural aggregates, it must meet specific quality standards. The primary challenges include the weak interfacial transition zone (ITZ) and high porosity of RCA, which negatively impact both fresh and hardened properties. Various treatment methods, including carbon dioxide treatment and impregnation with pozzolanic slurry, have been proposed to enhance RCA properties. This study investigates a novel and sustainable treatment material: recycled concrete powder (RCP). RCP, a by-product of RCA production, has been identified as a pozzolanic material and is evaluated for use in RCA impregnation, similar to other pozzolanic slurries. Unlike conventional pozzolanic slurry materials, RCP has not previously been explored for this purpose. Its application could significantly contribute to waste reduction and lower carbon dioxide emissions. The primary mechanism of pozzolanic slurry impregnation involves the reaction between pozzolans and calcium hydroxide (CH) within RCA. However, RCA sourced from older structures typically contains minimal or no CH due to prolonged exposure to environmental factors. Consequently, traditional pozzolanic slurry impregnation and carbon dioxide treatments may be ineffective for such RCA. To address this limitation, three treatment series were designed: (i) impregnation using only RCP, (ii) impregnation with a hybrid slurry comprising 75% RCP and 25% calcium hydroxide, and (iii) a two-step treatment involving immersion in a 14.2% calcium hydroxide solution followed by RCP impregnation. In all series, RCA (4–16 mm) was dried at 45 °C for 7 days before treatment to enhance slurry uptake. For the third series, an additional drying step was applied after calcium hydroxide immersion. The water-to-pozzolan ratios were set at 0.75 and 1.5, with a treatment duration of 2 hours for all series. After treatment, specimens were cured in an environment with 65% relative humidity at 20 °C for 14 days, followed by an additional 7-day drying period at 45 °C. To remove excess particles, the treated specimens were sieved through a 4 mm sieve. The characteristics of RCP, including pozzolanic activity index and particle size distribution, were evaluated. The effects of treatment on RCA were assessed through water absorption, density, and slurry uptake ratios. Additionally, the carbon dioxide emissions associated with each treatment method were analyzed and compared against improvements in RCA properties to identify the most sustainable and effective treatment approach. Scanning electron microscopy (SEM) was employed to examine the internal structure of untreated and treated RCA. The findings demonstrate that RCP is a viable material for slurry impregnation, offering significant benefits for waste management and sustainability. Moreover, this study introduces a novel approach for enhancing non-calcium hydroxide-bearing RCA by pre-treating it with calcium hydroxide before pozzolanic slurry impregnation. This method could enable the broader adoption of RCA in high-quality concrete applications, promoting a circular economy in the construction sector.

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Upcycling of Waste Glass into Porous Ceramics for the Degradation of Organic Pollutants in Wastewater

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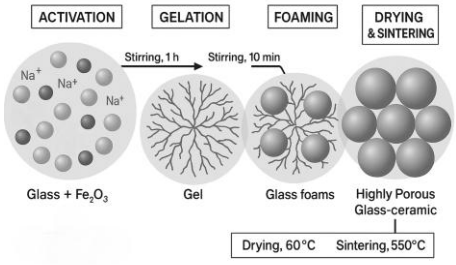
Keywords: Upcycling of waste glass, alkali activation, photocatalytic degradation, organic pollutant, visible light.

Many industrial companies provide the resources required for daily human activity. The large number of products produced by these industries generates a significant amount of waste. As the human population is growing, the generation of waste from industries is also growing. As a result, different solutions are needed to address pollution and waste disposal issues. Nowadays, these wastes are considered an opportunity, and they are referred to as by-products since they can be repurposed to create new materials. The upcycling revolution demands redefining waste by transforming industrial waste into renewable resources for many applications. Wastes from different industries can be used as a source of catalysts, porous glass ceramics, construction materials, etc. The main challenge for researchers is to determine whether waste can be converted into valuable resources for the future. This question motivates technology in several industries. Every year, approximately seven million tons of waste glass are sent to landfills without any significant reuse. Many end-of-life containers are deemed unrecyclable due to strict regulations on their chemical composition and purity. Upcycling offers a sustainable and energy-efficient alternative by transforming these discarded glass containers into valuable products. The present investigation aims towards upcycling the waste pharmaceutical glass in a borosilicate system into various porous ceramics, starting from the fine glass powders, consisting of 50–70 wt%, suspended in alkaline solution (3M NaOH/KOH). The prepared suspensions are then combined with photoactive compounds such as TiO_2 and Fe_2O_3 for potential applications in water treatment. The suspensions are vigorously stirred during the early stages of hardening, induced by the interaction of glass and the alkaline activator. The gel phase is essential for the consolidation even at ~Tg (550 °C, by thermal decomposition of the gel phase) instead of viscous flow sintering of glass, which is thoroughly optimized by thermogravimetric analysis. The resulting green bodies are first cured at 60° C for 72 hours and then sintered at 550–700°C to form porous structures.



This study also focuses on utilizing visible light instead of UV light because visible light photocatalysis utilizes approximately more than 40% of sunlight which is environmentally friendly and more sustainable. The activity of the photocatalytic degradation reaction depends on many factors, such as adsorption of dye

at the catalyst surface, band-gap energy, surface area, particle size, crystallinity, and electron–hole recombination rate. The interactions between the prepared matrix of waste glass, TiO_2 and Fe_2O_3 lead to the formation of new mixed-phase compounds with lower band gaps, the overall band gap of the composite decreases. The band gap shifts to a lower value, the composite starts to utilize visible light more effectively. The green porous structures exhibit over 75% open porosity and successfully pass the leaching test, as confirmed by ICP analysis. Furthermore, the porous structures containing TiO_2 and Fe_2O_3 additives demonstrate excellent photocatalytic activity and reusability for the photodegradation of organic pollutants when exposed to visible-light irradiation. Considering all these factors the research goals of this study are:

1. Upcycle industrial waste into a valuable product for reducing land and water pollution.
2. Prepare a porous glass ceramics catalyst which can have the ability to adsorb and degrade the organic pollutants from the wastewater.
3. Lowering the gap energy of overall composite from UV region to Visible region

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Utilizing Construction Demolition Waste Aggregates in Cement-Free Concrete for 3D Printing

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Keywords: Low CO_2 Concrete; Construction Demolition Waste Aggregate (CDWA), Supplementary Cementitious Materials (SCM); Additive Manufacturing.

The rising CO_2 emissions released into the atmosphere is a well-known environmental issue, with the construction sector being a major contributor. According to the Circular Economy Action Plan, construction sector accounts for over 35% of the EU's total waste and greenhouse gas (GHG) emissions, largely due to the production of materials such as cement and ceramics. Recognizing this, the European Green Deal emphasizes the need for energy-intensive industries like construction to reduce emissions and transition toward more sustainable practices.

3D concrete printing (3DCP) is an emerging technology that can minimize material use and waste trough optimized geometry. Currently, many 3DCP projects primarily serve as stay-in-place formworks, with load-bearing capacity still provided by traditional reinforced concrete. Most existing 3DPC formulations contains large amounts of cement – a major source of CO_2 emissions. From an environmental perspective, it is crucial to develop mixtures for 3DPC with reduced environmental impact, particularly in applications where lower mechanical properties are sufficient. This can be achieved by reducing cement content or incorporating alternative aggregates.

To address this issue, this study developed multiple low-CO_2 mixtures suitable for 3DCP by replacing cement with industrial waste ash as a binder and incorporating construction demolition waste aggregate (CDWA). High-calcium oil shale ash (OSA), which exhibits self-cementing properties, was used as a cement replacement. To enhance its binding properties, OSA was combined with a pozzolanic waste material – metakaolin (MK).

Two types of CDWAs were sourced from different construction and demolition waste landfills and compared to commercially available natural coarse aggregate (NCA) of dolomite to assess performance differences. NCA had an apparent density of ~2700 kg/m³ and a relatively low water absorption of ~2.0%. Both RWAs had slightly lower densities of ~2600–2650 kg/m³ and significantly higher water absorption of ~9.0%. Additionally, the RWAs contained a notable amount of fine dust particles, as well as traces of organic compounds and bitumen.

All three aggregate types were used in the 2/8 mm fraction. Granulometric analysis showed nearly identical particle size distributions (PSD) between the RWAs, with only slight variations compared to the NCA. This ensured comparable packing densities across all mixtures while maintaining consistent sand and binder proportions, leading to similar workability and water demand.

First, three series of cement-containing mixtures were formulated using NCA and both types of RWAs, with a binder composition of 60 wt% OPC, 25 wt% OSA, and 15 wt% MK. Then, for each cement-containing mixture, a corresponding cement-free mixture was formulated, where the binder consisted of 80 wt% OSA and 20 wt% MK. In total, six different series were tested for both cast and 3D-printed

specimens. 3DCP was carried out using a gantry-type printer, with each mixture printed into a square-shaped element. After hardening, the printed objects were sawn into prismatic specimens of 40×40×160 mm for flexural and compressive strength tests, which were performed in print direction. Additionally, cast specimens of the same dimensions were prepared from the same batch for comparison.

Cement-containing mixtures showed hardened state densities of ~2150 – 2250 kg/m³, while cement-free mixtures had slightly lower densities of ~2050 – 2150 kg/m³. The density results showed negligible differences between cast and 3D-printed specimens.

For all series containing cement, the samples achieved flexural strengths ranging ~5.5 – 7.5 MPa, while cement-free mixtures exhibited strengths of ~2.5 – 4.5 MPa. Surprisingly, the 3D-printed samples consistently outperformed their cast versions by at least 20% across all mixtures. Visual observation of the samples revealed that the aggregate distribution in cast specimens was more random, while the extrusion process of 3DCP led to a more structured arrangement of relatively large aggregate particles. This could have contributed to a stronger interlocking effect, improving stress transfer under bending loads. Similar findings have been reported in studies on conventionally cast concrete, which suggest that larger particles enhance load transfer and crack bridging.

The compressive strength results showed a significant difference between cement-based and cement-free samples. As expected, the presence of cement led to higher compressive strengths of ~50–65 MPa. Despite the absence of cement, the cement-free mixtures still achieved strengths of ~30 MPa, which falls within the range of normal-strength concrete. This suggests that the combination of OSA and MK can provide sufficient structural integrity even without cement.

Interestingly, in all cases, whether with or without cement, the differences in compressive and flexural strength results between formulations using NCA and CDWA were minimal. Although 3DCP samples exhibited ~15% lower compressive strength compared to cast specimens, the cement-free 3DCP mixtures with CDWA still demonstrated unexpectedly high compressive strength, making them suitable for various 3DCP applications, such as stay-in-place formwork, non-load-bearing structures, and even low-rise buildings.

Lyfe cycle analysis results showed that the majority of the emission reduction comes from cement replacement, by reducing ~80-90%. The use of CDWA contributed to a smaller reduction when compared to mixtures with NCA.

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Valorization of Industrial Wastes in Cementitious Composites for Carbon Sequestration and Structural Supercapacitor: A Waste-to-Energy Approach Towards a Circular Economy

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Keywords: Cementitious Composites; CO_2 Sequestration; Structural Supercapacitor; Industrial Wastes; Circular Economy.

Abstract: Climate change demands an urgent reduction in CO_2 emissions to address global warming. Another factor to address climate change is the mitigation of landfill pollution, as these landfills caused by disposal of industrial wastes contributing to greenhouse gas (GHG) emissions and environmental degradation. Additionally, utilization of non-renewable energy resources in the construction industry significantly increases CO_2 emissions leading to climate change. There are several sustainable solutions such as carbon capture and net-zero building technologies to promote decarbonization in the construction industry. A waste-to-energy approach towards a circular economy offers dual functional characteristics like carbon sequestration and structural supercapacitor by valorization of industrial by-products in cementitious composites. The reactive nature of these materials facilitates mineral carbonation, enabling the sequestration of CO_2 as stable carbonates, simultaneously, these composites are designed to exhibit excellent energy storage capabilities in combination with conductive materials such as graphene nanoplatelets (GNP), graphene oxide (GO), carbon black (CB) and carbon nanotubes (CNTs).
This paper provides a review of a diverse range of literature from peer reviewed Web of Science (WoS) and Scopus journals published in last five years, examining the integration of waste-derived materials including steel slag (SS), granulated blast furnace slag (GBFS), fly ash (FA), glass waste powder (GWP) and biomass waste (BW) into cementitious matrices to develop multifunctional composites capable of CO_2 and energy storage. The narrative review approach was adopted to comprehensively analyze the previous experimental findings representing the physio-chemical interactions of industrial wastes with cementitious matrices during hydration process, their potential of sequestering CO_2 inside cement matrix and enhancement of electrochemical performance. The discussion is structured thematically, covering mechanical properties, microstructural characteristics and material characterization for carbon capture efficiency, and energy storage capabilities forming multifunctional structural supercapacitors. Furthermore, the mechanisms of

CO_2 capture, energy storage and charging/discharging have inclusively been discussed. By integrating insights from recent experimental studies and theoretical advancements, this paper provides a holistic perspective on the sustainable utilization of waste resources in cementitious applications and highlights future research opportunities in carbon-negative and energy-efficient construction materials. The major findings of this study revealed that cementitious composites integrated with industrial waste as supplementary cementing material (SCM) possess the capability to sequester CO_2 while simultaneously working as both electrode materials and electrolyte pastes for structural supercapacitors. In terms of mechanical properties and CO_2 sequestration characteristics, the findings demonstrated that the incorporation of 10% of SS in cement enhances the 28-day compressive strength up to 23%, meanwhile offering 12% CO_2 uptake efficiency. Moreover, cement composites containing 10 to 20% of SS and GBFS do not significantly increase the compressive strength. However, they facilitate 22 to 39% calcium carbonation through direct CO_2 mineralization method. In contrast, the calcium leaching culminated up to 51% by using an indirect method. From the electrochemical performance and microstructural assessment, the results showcased that electrode composed of 20% steel slag, 10% GBFS in magnesium phosphate cement depicted the highest electrical conductance of 9.48 x 10^5 S. While the cement-based electrolyte pastes composed of 20% SS and 10% WGP integrated with polycarboxylate superplasticizer results in densely flocculated hydration products, small fibrous calcium-silicate-hydrate (C-S-H) gel. This composition depicted an evident increment in pore volume leading to enhanced ion concentration. As a result, the electrical conductivity and areal capacitance improved by 118% and 84% respectively, compared to normal cement pastes, boosting overall energy storage performance. In conclusion, SS outperforms other industrial wastes including FA, GGBFS, WGP and BW in terms of CO_2 and energy storage. The SS integrated with cement produces calcium silicate compounds majorly dicalcium silicate (C_2S) during hydration process demonstrate its significant potential as SCM. Its high reactivity enables its utilization as potential feedstock for CO_2 sequestration by mineral carbonation. Moreover, its iron (Fe) compounds make it well-suited for both cement-based electrodes and electrolyte pastes. Overall, this review highlights the benefits of a circular economy by repurposing industrial waste for decarbonization through carbon capture technology and renewable energy storage into infrastructures & built environments, advancing the development of structural supercapacitors in sustainable construction.

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Volume 1

Section 1.6: Structural Design and Durability

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μ-CT investigation on the influence of the spraying process on the air pore formation of optimized shotcrete mixes

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Keywords: Porosity, Durability,

Micro-computed tomography, Optimized mix design, Shotcrete. In the context of decarbonization, shotcrete as a permanent lining offers significant advantages over traditionally cast, multi-layer linings by reducing material consumption, which in turn lowers CO_2 equivalent emissions and global warming potential (GWP). Given the environmental impact of cement production, optimizing shotcrete mixtures is a crucial strategy for reducing its carbon footprint. A promising approach to lowering cement content involves incorporating supplementary cementitious materials (SCMs) such as fillers, ground granulated blast furnace slag (GGBFS), and performing a sieve line optimisation over the whole range of particles in shotcrete from micro- to macro grains. The mentioned materials help to enhance the packing density and overall performance of the resulting shotcrete. Preliminary investigations have indicated that the dosage of the accelerator may contribute to increased air pore formation on the shotcrete matrix; however, a more systematic and controlled investigation is required to confirm and quantify this observed behaviour. Therefore, this study focuses on the impact of the spraying process and accelerator dosage on the air pore formation of optimized shotcrete mixes. Furthermore, in the context of concrete decarbonation, the mix design was based on the Dinger-Funk sieve line optimization method over the full range of the particle size combined with clinker reduction and SCMs, fillers, and fine sand. Thus, it was possible to design sprayed concrete containing as little as 220 kg/m³ of ordinary Portland cement. Another key area of investigation is the effect of the spraying process on the final air content of shotcrete. The influence of spraying on air void distribution remains a subject of debate. Some researchers argue that the compaction effect during spraying reduces air content, whereas others suggest that the process introduces additional air, increasing porosity and potentially compromising durability. To address these conflicting perspectives, this study examines how spraying influences air void distribution at different stages and under varying process conditions. Samples were collected and analysed under three conditions: (I) conventionally cast, (II) sprayed without an accelerator, and (III) sprayed with an accelerator. Additionally, two key spraying parameters were assessed: (A) accelerator dosage (0%, 7%, and 10%) and (B) spraying speed (10 and 18 m³/h). Air content was measured in both fresh and hardened states. In the fresh state, air content was assessed before and after spraying, and the sprayed samples were tested without an accelerator. After hardening, porosity was evaluated using micro-computed tomography (μ-CT). The μ-CT assessment was conducted through a collaboration between TU Graz and the Synchrotron facility in Grenoble, France. A total of ten specimens, each measuring 23 × 75 mm² (⌀ × h), were scanned with a voxel resolution of 6.5 μm. The acquired data

were processed using threshold segmentation, a widely adopted method in civil engineering for analysing porosity and microstructural characteristics. By examining the combined effects of mix design optimization and spraying parameters, this study aims to provide deeper insights into shotcrete porosity and air void distribution. The findings will contribute to a better understanding of how to enhance the performance and durability of sprayed concrete while reducing its environmental impact

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3D printing of silica aerogel-based thermal insulation

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Keywords: Silica aerogel, Thermal insulation, Bio-slurry, Waste composites, 3D printing.

Global warming is a major concern of the 21st century, primarily caused by Greenhouse Gases (GHG). To limit temperature rise, we need to address these emissions, especially in the energy sector who represents 34% of the total share. Within this sector, a significant portion (25%) comes from controlling building temperatures. Improving thermal insulation and reusing resources can help enhance temperature control and reduce GHG emissions.

On one hand, silica aerogel is the best thermal insulator available. Usually describes as a material mainly composed of air and a Si-O-Si 3D network creating pores, silica aerogel exhibits the best thermal conductivity values ranging from 0.012 to 0.020 $W.m^{-1}.K^{-1}$ but it's not widely used mainly due to high costs, complex synthesis and physical properties like fragility and volatility. To make the most of silica aerogel, we need to bind it and tackle its physical properties. On the other hand, developing biobased and biodegradable binders, preferably from waste materials, is an effective way to lower the GHG and therefore is crucial to develop. These binders are most of the time combined with other biobased materials due to the affinity. Investigating its use to a broader range of materials is therefore a good option.

A previous study showed the capacity of producing these silica aerogel bio-waste composites, with competitive thermal conductivity and with sufficient mechanical strength to meet the standard. Therefore, this study investigates the printability of said thermal insulating composites. An emphasis on the impact of the printing on the properties, mainly thermal insulation and strength, will be made. Additionally, one of the targeted application is the simultaneous printability of the concrete and thermal insulation layer. Therefore, the behaviour between of 3D printed concrete layers and the slurry is investigated. Adhesion and simultaneous drying will be investigated.

Figure 13: 3D printed layers. a) Bio slurry for thermal insulation - b) Fresh cement and fresh bio slurry.

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Abrasion Resistance of Concrete made with Harvested and Traditional fly ash

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Keywords: wear resistance, compressive strength, durability, interrupted curing, traditional fly ash

Concrete durability is a critical factor in ensuring the long-term performance of structures, particularly in applications subject to mechanical wear. The incorporation of fly ash as a partial cement replacement is widely recognized for its potential to enhance the mechanical and durability properties of concrete while promoting sustainability through waste utilization. However, the performance of harvested fly ash (HFA) compared to traditional fly ash (TFA) remains an area of ongoing research. This study investigates the abrasion resistance and compressive strength of concrete containing 20% cement replacement with harvested fly ash (HFA20) and traditional fly ash (TFA20) under different curing conditions, providing insights into the influence of curing methods on mechanical and durability properties.

Concrete mixtures were prepared with a constant water-to-cementitious ratio and a 20% fly ash replacement level. The specimens were subjected to three distinct curing regimes: continuous moist curing (standard curing in water until testing), interrupted curing (moist curing for 4 or 7 days followed by 3 days of air-dry curing, denoted as 4M3D and 7M3D, respectively), and full air-dry curing after the initial curing period. Compressive strength was assessed at multiple curing ages to evaluate the development of mechanical properties, while abrasion resistance was determined using a rotating disk method. The parameters analyzed included wear depth, abrasion rate, coefficient of variation, and abrasion index. The relationships between compressive strength and abrasion resistance were examined to establish correlations between mechanical and durability performance.

The results indicate that the TFA20 mixture exhibited superior performance in both compressive strength and abrasion resistance compared to the HFA20 mixture across all curing conditions. Continuous moist curing produced the highest compressive strength values and the lowest wear depth, demonstrating the positive influence of sustained hydration on cementitious materials. Interrupted curing led to intermediate performance, with the 7M3D condition yielding better results than 4M3D, highlighting the importance of extended moist curing before exposure to air drying. In contrast, air-dry curing resulted in the weakest compressive strength and the highest wear depth, indicating that inadequate curing significantly compromises both strength development and abrasion resistance.

A strong correlation between compressive strength and wear depth was observed, confirming that higher strength generally translates to improved resistance to surface degradation. The abrasion rate followed an inverse trend with compressive strength, reinforcing the critical role of material integrity in wear performance. The coefficient of variation in abrasion tests remained within acceptable limits, ensuring the reliability of experimental measurements.

This study underscores the necessity of optimizing fly ash selection and curing conditions to enhance the durability and mechanical properties of concrete. The findings contribute to the development of sustainable, high-performance construction materials by demonstrating the influence of fly ash type and curing practices on concrete's resistance to mechanical wear. These insights are particularly valuable for infrastructure exposed to high abrasion demands, such as pavements and industrial floors. Further research is recommended to explore the long-term performance of harvested fly ash mixtures in various environmental conditions.

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An Investigation into the Potential of Hempcrete for 3D Printing of Shell Structures

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Keywords: Hempcrete, Mix Design, Shell Structures, Extrusion-based 3D Printing, Digital Fabrication

Abstract:
This study advances sustainable construction by developing a novel hempcrete mix specifically engineered for extrusion-based 3D printing of freeform shell structures. Recognizing the environmental limitations of Portland cement and the underexplored potential of bio-based materials in additive manufacturing, a performance-based, iterative methodology was adopted to optimize fresh-state properties essential for printability. The final mix—comprising the mass ratio of lime : water : dried hemp shives (pre-wetted to account for 523% water absorption) is: 25:12.5:1 and sodium carbonate is added as an accelerator at 2% by the mass of lime. This demonstrated enhanced setting time, extrusion stability, and buildability, achieving buildability of 25 printed layers without structural failure.
A robotic printing systematic investigation with small-scale model structures were carried out using a pressurized extrusion printing system mounted on a six-axis industrial robotic arm (KUKA KR6 Agilus). The toolpaths were generated using simple slicer within computational design software (Rhino3d + Grasshopper). This validated the mix's compatibility with digital fabrication processes and allowed the identification of geometry constraints and optimum print variables such as layer height, nozzle size, extrusion pressure, extrusion speed and feed rate of the robot. An extrusion pressure of 1 bar paired with a printing speed of 0.25 m/s offered the most consistent results, while a 40% compaction height proved effective for interlayer bonding. The printed samples revealed strong correlation between digital design and physical output, with minimal deviation in geometry and no visible deformation. Despite material loading challenges and limited open time, the results confirm sodium carbonate as a viable accelerator for lime-based systems, offering improved print performance while maintaining early mechanical integrity. This research establishes a new material pathway for printable, low-carbon composites and demonstrates the feasibility of formwork-free, digitally driven construction using renewable, regionally sourced materials.

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Analysis of Time-Dependent Deflection & Flexural Performance of LC3 and OPC Concrete Beams

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Keywords: Flexural Strength, Immediate Deflection, Long-Term Deflection, Limestone Calcined Clay Cement (LC^3), Structural Elements, Beam Testing

Abstract - Limestone Calcined Clay Cement (LC^3) is increasingly being adopted in the construction industry as a sustainable alternative to reduce carbon emissions, given that Ordinary Portland Cement (OPC) is responsible for approximately 8% of global anthropogenic carbon dioxide emissions. LC^3 represents one of the most active areas of research worldwide. However, further investigation is required, particularly involving large structural elements, to evaluate their structural integrity for large-scale construction applications. This study aims to assess the structural performance of LC^3-based concrete, focusing on beams due to their critical role in load distribution within structural systems. The research offers valuable insights to support both academic studies and commercial adoption, helping to build confidence in the use of LC^3 for structural elements. A comparative analysis was conducted between LC^3 and OPC-based concrete, with deflection measured using two methods. Initially, mechanical tests; including compressive strength (ASTM C39) and splitting tensile strength (ASTM C496) were performed after 28days of curing. Flexural strength tests were carried out using a Universal Testing Machine (UTM), with deflection recorded under incremental loading as per ASTM C293. To compare the long-term behavior of the two concrete types under sustained loading, concrete blocks weighing 6 tons were placed on the beams for 52 days, and deflection was monitored using a Laser Distance Meter. Two rectangular beams having cross-section of 150 mm x 200 mm and span length of 2.13 meters were cast, with OPC and the other with LC^3. LC^3-based concrete demonstrated higher compressive and flexural strength than OPC and exhibited lower immediate deflection. Over the long term, both materials showed similar deflection behavior. These results suggest that LC^3 not only offers enhanced early-age performance but also ensures long-term structural reliability, reinforcing its potential as a viable and sustainable alternative to OPC in structural applications.

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Application of interpretable machine learning driven by physical and chemical information for predicting and optimizing the sulfate resistance performance of concrete

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Keywords: Sulfate attack, machine learning, multi-objective optimization, PCINNs

As global infrastructure ages and the demand for durable buildings increases, understanding and accurately predicting sulfate attack behavior has become critical. Sulfate attack is a primary cause of concrete degradation, leading to expansion, cracking, and reduced performance. These effects not only compromise the structural strength and service life of buildings but also increase maintenance costs, ultimately affecting both the economic viability and environmental sustainability of construction projects. Therefore, accurately predicting the expansion behavior of concrete under sulfate attack is essential for designing long-lasting and durable concrete structures.

This study addresses this challenge by developing predictive models based on 2,525 expansion measurements of mortar and concrete exposed to various sulfate attack conditions. Four machine learning algorithms—Kernel Ridge Regression (KRR), Random Forest (RF), Extreme Gradient Boosting (XGBoost), and Multi-Layer Perceptron (MLP)—were employed to construct and compare the models. The results indicate that the MLP model provides the highest prediction accuracy, making it the most reliable model for this task.

To enhance the interpretability of the MLP model, the Shapley Additive Explanations (SHAP) method was used to identify the key factors influencing concrete expansion. Furthermore, a multi-objective optimization model was developed by combining the MLP model with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). The aim of this optimization was to balance sulfate resistance, global warming potential (GWP), and life cycle cost (LCC) in concrete mix designs. For a sulfate attack concentration of 5%, the optimized mix design achieved an expansion value of 0.018% after 360 days, with a GWP of 225 kg/m³ and an LCC of 368 yuan/m³. This approach provides a comprehensive framework for improving concrete durability.

Considering the complex chemical reactions involved in sulfate ion transport, the nonlinear partial differential equations (PDEs) governing this process are difficult to solve analytically. This challenge limits the accuracy of sulfate attack severity assessments and the precision of predictions. To address this issue, the study integrates physical and chemical information into machine learning, developing a Physics-Chemical-Informed Neural Networks (PCINNs) method capable of solving the nonlinear PDEs governing sulfate attack. This method successfully resolves both forward and inverse problems in sulfate transport prediction.

The forward problem involves predicting sulfate concentrations at various depths during the later stages of attack, using known sulfate transport coefficients and limited or no early-stage concentration data. In contrast, the inverse problem requires calculating sulfate transport coefficients and predicting sulfate concentrations at different depths, based on early-stage concentration data. The results demonstrate that the PCINNs method outperforms traditional methods, such as the Finite Element Method (FEM), in predicting sulfate diffusion coefficients. In forward calculations, the error in sulfate concentration predictions remains below 0.1%. In inverse calculations, under noise-free conditions, the estimation error for the transport coefficient is less than 1%, and even with 5% noise introduced, the error remains below 3%.

These findings emphasize the robustness and high accuracy of the PCINNs method, even in the presence of noisy data, and highlight its superior performance compared to traditional methods.

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Carbon-Reduced High-Performance Foamed Concrete: Design, Fabrication, and Multi-Scale Properties

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Keywords: High-performance foamed concrete; Carbon reduction; Carbonation enhancement; CO_2 foam; Material properties

The world is facing severe environmental challenges due to CO_2 emissions. In response, this study develops a high-strength carbon sequestration foamed concrete (HPFC) aimed at maximizing CO_2 storage and utilization. The HPFC is prepared by introducing stable CO_2 foam into a densely packed cementitious matrix designed based on particle packing theory, followed by carbonation curing to enhance its performance and achieve CO_2 sequestration. The results show that HPFC prepared with 20% CO_2 concentration in foam exhibits superior performance, with twice the strength of conventional foamed concrete, excellent durability, and low thermal conductivity. The CO_2 foam not only induces internal carbonation, further improving HPFC properties, but also facilitates external carbonation, enhancing the overall material performance. Carbonation curing significantly increases the compressive strength and microhardness of HPFC, leading to low water absorption and high resistivity, demonstrating exceptional durability. This is attributed to carbonation products effectively filling microcracks and pores, thus improving microhardness and long-term stability. Moreover, the developed HPFC exhibits remarkable carbon capture capacity, sequestering approximately 90 kg of CO_2 per cubic meter through carbonation curing. Thermal conductivity simulations indicate that the designed HPFC has significant energy-saving potential, reducing electricity consumption or carbon emissions by 20%. Therefore, this innovative concrete material offers a promising strategy for advancing sustainable construction practices and contributing to carbon neutrality goals.

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Combined effect of wet-dry cycles and UV light on the yarn-matrix interface of Textile Reinforced Concrete

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Keywords: textile reinforced concrete, composite, matrix, bond, interface, textile

Textile Reinforced Concrete (TRC) is an emerging cementitious composite reinforced with textiles made of carbon, basalt, or AR-glass. The TRC with textile reinforcement above critical volume fraction provides a better strain-hardening type response thus offering high strength-to-weight ratio with improved ductility. Such behaviour of TRC generates closely spaced fine cracks (<0.2 mm) up to failure strains. Its non-metallic reinforcement mitigates corrosion, allowing thin-sectioned TRC elements in harsh environments like water retaining structures, wastewater treatment plants, and marine structures. The load-bearing characteristics of TRC majorly depend on the interfacial bond between the cementitious matrix and the yarn or strand, achieved through adhesion between outer filaments and the matrix, and internal filament bonds. The yarn-matrix bond behavior is influenced by coating impregnation, matrix penetration, and environmental factors like humidity and temperature. The flaws in coatings, relative humidity, temperature, and sustained stresses at the interface can alter bonding characteristics. In water retaining structures, cracked TRC faces the challenges from wetting-drying cycles, UV exposure, and temperature variations. Wet-dry cycles arise from the changes in water level whereas temperature cycles arise from variations in ambient temperature during day and night. For instance during summer (mid of march to mid of June) the temperature ranges from 26°C at night and 45°C during day in Jhansi, India.
This study investigates the effects of wet-dry cycles and UV light on the yarn-matrix interface in cracked TRC. E-glass textile yarns coated with styrene-butadiene rubber are used as reinforcement, while slag-based fine-grained mortar serves as the matrix. The mortar composition mimics practical concrete mixes used in water retaining structures, targeting an average compressive strength of 50 MPa and an alkaline environment with a pH of 12.5. To benefit the E-glass reinforcement, a minimum of 70% slag is incorporated. Two series of test specimens are considered: one series is moist cured for 28 days, and the other series is moist cured for 28 days and exposed to wet-dry cycles and UV light under stress. The wet-dry cycles involve 6 hours of wetting followed by 6 hours of drying at 50°C. Stress is applied to the yarn using a calibrated torque system, straining it up to 0.8 mm, which is about 30% of its tensile strain capacity. Microstructural analysis using SEM assesses defects on coatings and damage to filaments, while pull-out tests correlate mechanical responses with microstructural characteristics.

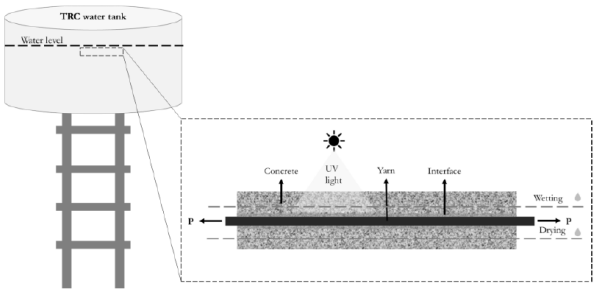

Figure 1. Schematic representation of TRC exposed to wet-dry cycles and UV light under stress

It is evident from previous studies that microstructural analysis that even though there exist surface defects on the coatings of virgin textile yarns, these defects become more severe after embedding in the cement

matrix exposed normal curing conditions. This could be caused by the aggressive precipitation of cement hydrates such as portlandite and ettringite. In the current study, preliminary studies on the textiles confirm that coating is not fully impregnated and observed some micro defects. The mechanical and microstructural characterization of textiles and TRC specimens is in progress and results are expected to be promising that could provide better insights for durability of TRC sections.

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Comb-like poly(carboxylate ether) copolymers (PCEs) as inorganic pigment dispersants in waterborne coating formulations

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Keywords: Waterborne coating, waterborne emulsion paints, pigment dispersant, comb-like copolymer, poly(carboxylate ether) (PCE).

Pigment dispersants are essential for enhancing the dispersion of inorganic pigments, especially in waterborne coatings. Due to water's high surface tension, pigment aggregation is more pronounced in waterborne systems than in solvent-borne ones. Polyanionic dispersants provide electrostatic stabilization, but as the coating dries and water evaporates, the system's polarity decreases, causing the dispersant to lose ionization and reduce pigment stability, leading to aggregation. Conventional dispersing agents also negatively affect the water resistance of final coatings.
Studies on poly(acrylic acid) derivatives show that branching reduces viscosity without affecting surface anchoring sites, preventing particle bridging and enhancing coating performance. Steric stabilization improves pigment stability, gloss, and opacity. Additionally, the lower ionic character might result in more hydrophobic coatings with enhanced anticorrosion properties. However, their synthesis via anionic or controlled radical copolymerization (ATRP, RAFT, NMP, Cu-mediated) limits industrial scalability.
Our group has studied the synthesis of poly(carboxylate ether) copolymers (PCEs), specifically methacrylic acid-co-poly(ethylene glycol methacrylate) (MAA-co-PEGMA) copolymers, via free-radical aqueous copolymerization. These MPEG-type PCEs have a comb-like structure, with an anionic carboxylic group backbone that enhances adsorption on inorganic pigment surfaces and non-ionic polyethylene glycol side chains that provide steric hindrance. Although PCEs with worm-like conformations are well-known as rheology modifiers and water reducers in the cement and concrete industry, we believe they could also be used as pigment dispersants and spacers, especially when PCEs have star-like conformation. This is due to the additional side chains, along with the anionic carboxylic groups.
While pigment-dispersant interactions have been studied since the late 20th century, few studies have directly examined their impact on formulated paint properties. In this work, PCEs with various characteristics are synthesized and incorporated into waterborne coating formulations. Their performance is evaluated by comparing the final film properties to reference standard paints.

Comb-like copolymers or PCEs were synthesized by free-radical copolymerization semibatchwise in aqueous solution using MAA and PEGMA as monomers. PCEs with several MAA/PEGMA ratios and different PEGMAs were used. Monomer conversion and copolymer cumulative composition were measured by ^{1}H-NMR. Homogeneous copolymer compositions were obtained in all experiments.

The efficiency of PCEs in dispersing inorganic pigments was analyzed by measuring the viscosity of a TiO_2 dispersion in water at various PCE concentrations, compared to a conventional dispersing agent (CDA).

Waterborne paints were formulated using the synthesized PCEs as dispersing agents. Paints formulated with binders of different functionalities, carboxylic acid and phosphate, were evaluated. Optical properties (gloss, surface roughness, and opacity) and water sensitivity (contact angle and water uptake) were analysed. The effect of PCEs was found to be dependent on the used binder.
Regarding the paints formulated with the carboxylic acid functionality binder, the optical properties important in decorative coatings were improved or maintained, indicating that the TiO_2 was dispersed at

least as effectively as when using a CDA. Additionally, the water sensitivity of the paint showed a significant improvement. On the other hand, when a phosphate-functionalized latex was used as binder and PCEs as dispersants, all optical properties were worsened compared to the paint where a CDA was incorporated, suggesting a poorer dispersion of TiO_2. However, properties related to protective coatings were significantly improved. The most significant improvement was achieved in corrosion protection when steel plates were coated with the paints formulated with phosphate functionality binder, and subjected to an accelerated corrosion test in a salt-spray chamber for 500 h (see **Figure 1**).

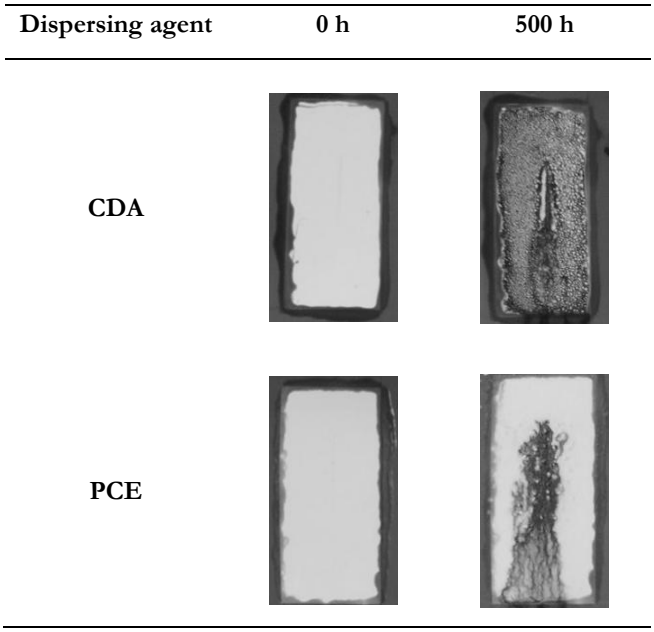

Figure 1. Evolution of corrosion for scribed specimens exposed to salty fog.

In this work, paints were successfully formulated by replacing conventional pigment dispersants with worm- and star-like PCEs. Although the final properties of the coatings were dependent on the binder's functionality, the overall use of the synthesized PCEs resulted in more hydrophobic films with enhanced protective performance. This improvement was likely due to the higher molecular weight of the copolymers, lower carboxylic acid concentration, and long side chains, that provide both stability and spacing to the system.

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Concrete performance and durability of low clinker – high filler binders in combination with pozzolanic materials

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Keywords: SCMs, low clinker, high filler, concrete, durability

European cement industry roadmap to achieve net zero carbon footprint by 2050 relies minimally on the leverage of clinker factor reduction. This mostly comes from the observation that most commonly known supplementary cementitious materials (SCMs) like fly ashes (FA) and ground granulated blastfurnace slag are available in that region in limited and decreasing volumes and the emerging ones, like calcined clays (CC), natural pozzolans (NP) and other industrial by-products, are still not largely available or not fully mastered. AS a direct consequence, low clinker – high SCM(s) binder cannot be envisioned as scalable solutions to achieve net zero by 2030. Yet a commonly used SCM in this industry has been disregarded for its (close to) absence of reactivity in a cementitious setting is ground limestone filler (LF). Therefore, we see that a reduction of the average clinker factor in European cements as opportunity to redirect LF feedstocks towards SCM use through sole and controlled grinding.
With that context in mind, this work proposes an approach to ternary binders made of low ordinary Portland clinker contents (<30%) and high limestone fillers (>40%) completed with pozzolanic materials being either a calcined clay (commercial metakaolin) or two different natural pozzolans. To achieve adequate performance both from a mechanical and a concrete durability standpoint, those binders need to be mixed with limited water contents. Therefore, the second essential pillar in this approach for low clinker – high filler binders rests on the formulation of mortars or concretes with water-to-binder (w/b) ratios not exceeding 0.4.
Firstly, those three distinct pozzolanic materials were first assessed in terms of: chemical composition (ICP-OES and ion chromatography), mineralogical composition (Rietveld refinement), particle size distribution by means of laser granulometry and reactivity by means of the R3 test (ASTM C1897-20).
Based on an extensive mortar testing campaign, we have settled for a binder composition combining CEM I, one of the pozzolanic material, the same limestone filler and completed where and in adequate amounts by calcium sulfate.
Then, said binder designs were implemented at concrete scale. Concrete formulation for each of the three binders were prepared with 350 kg/m3 of binder, a water-to-binder ratio of 0.35 and crushed limestone aggregates. Slump target of the concrete was set to S4 type of concrete, i.e. ideally presenting a slump between around 200 mm, which was achieved using high-range water reducing polymers commercially available. For the calcined clay based concrete exclusively, slump retention was measured for up to 90 minutes. For each of the three concrete mixes, cubic (10 cm x 10 cm x 10 cm) samples were prepared, cured for 24 hours in said moulds at 20°C, then demoulded and cured under water at the same temperature until testing. Strengths were measured after 1, 28 and 91 days of curing. All mixes presented 1 day strength above 10 MPa and ranging between 40 and 65 MPa at 28 days depending on the nature, the chemistry and the dosage of the pozzolanic material.
Further samples were moulded for each mix design to allow durability evaluations. Accelerated carbonation, performed at 3% CO_2 on 90 days water cured samples was performed for the calcined clay and the silica-rich natural pozzolan based concretes. Both concrete designs presented similar levels of carbonation rate, around 2.0 mm/√day which could be explained by complete consumption of portlandite in the case of the

calcined clay mix, as highlighted by TGA measurements, lack of reaction and therefore lack of porosity refinement in the case of the natural pozzolan, also highlighted indirectly by TGA measurements.
Chloride migration coefficients were determined after 28 days and 90 days curing on all three concrete mixes. The calcined clay based mix presented chloride migration coefficients below 1.0 $.10^{-13}$ m^2/s at all ages, further highlighting the high resistance of calcined clay based mixes in such environments. On the other hand, the silica-rich natural pozzolan based concrete presented relatively high values of chloride migration coefficients, further confirming the lack of porosity refinement due to the limited reactivity of said pozzolan at the measured age, that despite the improvement between 28 and 90 days. Eventually the silica-poor natural pozzolan presented an improved chloride migration coefficient which was also expected from the strength development at 28 days.
Resistance to external sulfate attack was determined on 90 days water cured samples of the calcined clay and the silica-poor natural pozzolan based concretes. Both calcined clay and natural pozzolan based concretes presented very good resistance to external sulfate attack with longitudinal extensions below 0.06‰, satisfying the highest exposure class (XA3) limit of 1.2‰.
This study targeted at demonstrating the feasibility of rapid and scalable implementation of low clinker – high filler concretes when prepared in combination with pozzolanic materials, provided an adequate understanding of both pozzolanic materials properties and capabilities as well as motivated concrete formulation practices relying on reduced water consumption.

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Conservation of Euville Limestone:

A Comparative Study of Water Transport Properties

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Keywords: built heritage, limestone, water transport, porous building materials, hydric properties

The intrinsic properties of building materials are critical to understanding their suitability for architectural and construction applications, performance, and durability. With a growing emphasis on sustainable architecture and materials conservation, studying water transport mechanisms in natural stone is particularly relevant, as liquid movement within the material influences its degradation, mechanical stability, and long-term preservation. Studying water transport in porous materials, such as limestones, is essential since it directly affects the selection of construction materials and conservation practices for historic buildings and monuments. This research investigates the hydric behaviour of a widely used limestone variety, examining the relationship between its structural characteristics and water transport properties. The Euville limestone is a material considered for its architectural and sculptural applications that are widespread in France, Belgium, and the Netherlands. This natural stone variety is examined to assess the relationship between the intrinsic characteristics of the material and the mechanisms of water transport.

A comprehensive experimental approach has been adopted to evaluate the water transport properties of the Euville limestone under controlled conditions. The study includes capillary water absorption tests and atmospheric pressure water uptake experiments to assess the material's capacity to absorb liquids. These tests allow for the estimation of open porosity, providing critical data on the microstructural characteristics of the stone. Likewise, the drying rate has been determined considering the contribution of moisture retention to degradation. In addition, a column experiment has been conducted to measure the water flow speed within the stone. The data derived from these experiments have been compared with results presented in the literature on similar limestone types, offering a broader perspective on the performance relative to other natural stones. Furthermore, to bridge the gap between laboratory-based analysis and real-world conditions, the Karsten tube test has been employed to evaluate water absorption in situ. This approach enables a direct comparison between non-destructive, on-site testing methods and traditional laboratory techniques, supporting an extensive assessment of water absorption behaviour in natural building materials and making the findings applicable in everyday practice.

The experimental results revealed some variations in the water transport properties of the Euville limestone, driven by its petrographic characteristics. The water absorption tests determine the water uptake capacity, which is 6% of the stone weight. In addition, though the acquired data, it has been possible to determine the open porosity which ranges from 10% to 15%. Another crucial property in terms of degradation is the drying speed assessment that has been addressed considering the first, and the second phases of drying that correspond to a water removal rate of 0.17 kg/m²h and 0.23 kg/m²h, respectively. Moreover, this reflected the influence of microstructure and, thus, of porosity, on the absorption and drying rates. The column experiment provides valuable data on the speed and distribution of water flow within the material, demonstrating the variability in natural materials such as limestones. The Karsten tube test further reinforces these findings, underscoring the importance of in situ testing to accurately assess water absorption of building materials. These experimental results have been contextualised within the existing

research on water transport in limestones, allowing for comparative analysis, underscoring the importance of material-specific studies and contributing to the understanding of limestone behaviour for improved material selection and conservation strategies.

This study highlights the relevance of characterising the water transport mechanisms of porous building materials, particularly natural stones used in façade decorations and monuments of buildings. The findings offer practical implications for the selection of conservative treatments for the Euville limestone, which has been used for historical constructions. In particular, the acquired results lay the groundwork for the understanding of the degradation mechanisms affecting this stone. Furthermore, the information gained are fundamental for the selection of a conservative treatment that can consolidate the stone with the ultimate aim of preventing its deterioration. The observed variability in water transport properties highlights the need for detailed material assessment to ensure appropriate application and preservation strategies. By integrating laboratory experiments with field-based evaluation methods, this research points out the material's heterogeneity due to its natural origin, underlining the necessity for a detailed characterisation in both research and practical applications.

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Effect of Longitudinal Rebar Ratio and Synthetic Fibre Dosage on Flexure-Shear Behaviour of GFRP Reinforced Concrete Beams

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Keywords: GFRP Beams, Polypropylene Fibres, Rebar Ratio, Flexure-Shear.

Non-metallic Glass Fibre Reinforced Polymer (GFRP) bars are widely used in construction across the globe in recent decades. The negative effect of the inherent brittleness of the GFRP bars on the serviceability can be alleviated by using different discrete fibres. However, limited studies are available to understand the effect of fibre addition on the flexure-shear behaviour of GFRP-Reinforced Concrete (RC) beams.
This study investigates the behaviour of GFRP-RC beams and Thermo-Mechanically Treated (TMT) RC beams tested at shear span to depth ratio(a/d) of 4.43 under 3-point loading and compares the same with each other. A rebar ratio of 0.37% is chosen for TMT RC beams so that this beam should be a under reinforced section and section can accommodate the GFRP rebars in single layer when equivalent rebar ratio is provided.
The GFRP rebar ratio used in this investigation is based on two factors, namely i) to study the behaviour for same rebar ratio and ii) to study the behaviour for rebar ratio which offers the same axial rigidity as of 0.37% TMT rebar ratio (equivalent rebar ratio). The later one is calculated as $(EA)_{TMT}=(EA)_{GFRP}$ and amounts to GFRP rebar ratio of 1.52%. For both type of reinforcements 12mm diameter rebars are used to avoid any unwanted variations. No beam had stirrups because it was aimed to focus on the contribution of fibres, rebar ratio and their combined effect on the behaviour when tested at a/d ratio of 4.43.
Total of eight RC beams are tested under 3-point loading with a shear span of 700mm. The a/d ratio used in the present investigation i.e., 4.43 falls between the pure flexure and pure shear failure modes as per Kani's theory. Therefore, it is expected that when beams are loaded, they develop flexural cracks followed by diagonal shear tension which is called as flexure-shear. Under this presumption the beams are evaluated for the effect of rebar ratio and fibre dosages (0%, 0.50%, and 1.0%) in terms of load-displacement response, peak load, deflection at failure, post cracking stiffness and failure modes. Also, the behaviour of GFRP and TMT RC beams is compared at different fibre dosages. The test matrix is as shown in

Table 5.

Table 5 Test Matrix

Specimen ID	Fibre dosage in %	Type of Rebar	Number of Rebars	Flexure Rebar Ratio
T37F00	Control	TMT	1	0.37
T37F50	0.5	TMT	1	0.37
T37F100	1.0	TMT	1	0.37
G37F00	Control	GFRP	1	0.37
G37F50	0.5	GFRP	1	0.37
G37F100	1.0	GFRP	1	0.37
G150F50	0.5	GFRP	4	1.52
G150F100	1.0	GFRP	4	1.52

All the 8 beams had dimensions as 150mm×200mm×1500mm (b×D×L). The side cover was 20mm and cover to the bottom of longitudinal bar was 36mm. During testing the beams were simply supported with

a clear span of 1400mm. The section details with the rebar arrangements and test configuration are as shown in **Figure 14**.

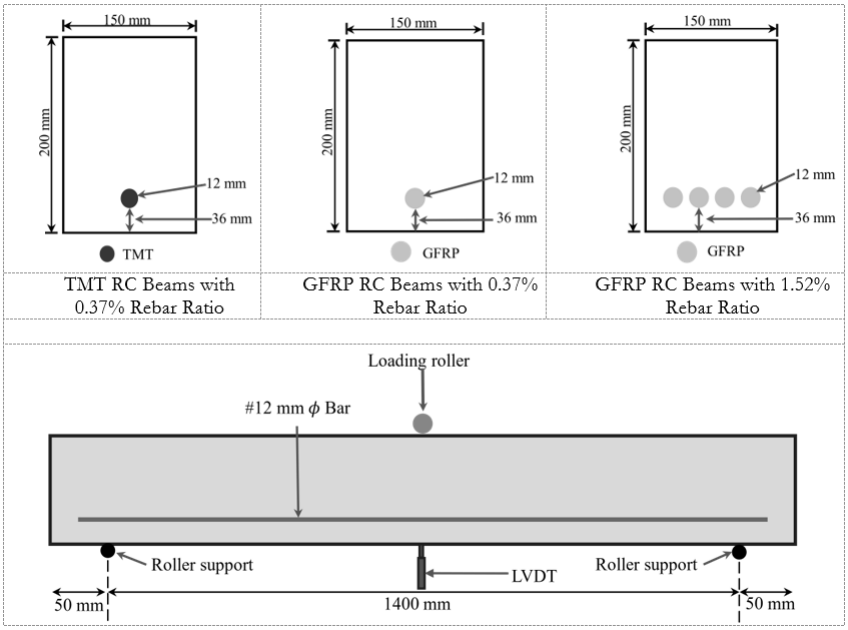

Figure 14 Rebar Configuration and Test Arrangement

Fibre Dosage effect

Table 6 Effect of Fibre Dosage

Specimen	Peak Load, P (kN)	% change in P	Deflection at Failure, Δ_f (mm)	% change in Δ_f	Post Cracking Stiffness	% change
T37 category						
T37F00	30.39	-	46.02	-	3.99	-
T37F50	31.77	4.54 (▲)	42.81	6.97 (▼)	5.01	25.56 (▲)
T37F100	36.68	20.69 (▲)	43.4	5.69 (▼)	5.26	31.82 (▲)

G37 category						
G37F00	27.20	-	41.56	-	1.55	-
G37F50	33.76	24.11 (▲)	38.39	7.62 (▼)	1.85	19.35 (▲)
G37F100	43.73	60.77 (▲)	29.7	28.53 (▼)	3.16	103.87 (▲)
G150 category (Fibre Dosage between 0.5% and 1.0% only)						
G150F50	50.80	-	14.03	-	5.27	-
G150F100	59.87	17.85 (▲)	16.63	18.53 (▲)	5.46	3.60 (▲)

Effect of Rebar Ratio

Table 7 Effect of Rebar Ratio and Comparison with TMT

Specimen	**Peak Load, P (kN)**	**% change in P**	**Deflection at Failure, Δ_f (mm)**	**% change in Δ_f**	**Post Cracking Stiffness**	**% change**
Control Specimens						
T37F00	30.39	-	46.02	-	3.99	-
G37F00	27.2	10.49 (▼)	41.56	9.69 (▼)	1.55	61.15 (▼)
0.5% Fibre Dosage						
T37F50	31.77	-	42.81	-	5.01	-
G37F50	33.76	6.26 (▲)	38.39	10.32 (▼)	1.85	63.07 (▼)
G150F50	50.8	59.89 (▲)	14.03	67.22 (▼)	5.27	5.18 (▲)
1.0% Fibre Dosage						
T37F100	36.68	-	43.4	-	5.26	-
G37F100	43.73	19.22 (▲)	29.7	31.56 (▼)	3.16	39.92 (▼)
G150F100	59.87	63.22 (▲)	16.63	61.68 (▼)	5.46	3.82 (▲)

The test results reveal that the fibre dosage in TMT RC Beam and GFRP RC beam with 0.37% rebar ratio has significant contribution to the post cracking stiffness and failure modes. In GFRP RC beams with 0.37% rebar ratio failure transitioned from brittle to pseudo ductile flexure failure. As the rebar ratio increased in the GFRP RC beams the fibres had minor increment in post cracking stiffness and no effect on the failure mode. From the results it can be concluded that increasing the fibre dosage in GFRP RC beams can overcome the inherent brittleness and improve the serviceability, but it is applicable only to tension-controlled RC beams. Increasing the fibre dosage in compression controlled GFRP RC beams will have insignificant effect on the serviceability and failure modes. Therefore, increasing fibre dosage in tension controlled GFRP RC beam one can reduce the number of cracks, width of the cracks, failure mode and increase the warning time before failure.

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Development of sustainable building materials with the guidance of nanoscience and nanotechnology

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Keywords: Nanoscience, Nanotechnology, building materials, sustainable, concrete.

Nanoscience studies the nature and characteristics of materials at the atomic and molecular scales; nanotechnology is a method of assembling, modulating, and modifying the structure of materials at the nanoscale, leading to the modulation of macroscopic properties. In recent years, the application of nanoscience and nanotechnology in sustainable building materials research has also developed rapidly. This report introduces the research progress of our team from two aspects. In terms of nanoscience, this report focuses on the application of first-principle and molecular dynamics simulations to study the changing law of the hydration process of tricalcium silicate, an important component of cement, at the atomic and molecular scales. First-principle calculations reveal that the mechanism of water adsorption on the surface of tricalcium silicate is mainly due to the transfer of electrons from the valence band maximum of the tricalcium silicate surface to the lowest vacant orbitals of the water molecules, which raises the Fermi energy level and moves the bonded molecular orbitals downward. Water adsorption, proton exchange and diffusion of water to the surface layer gradually accelerate the leaching of calcium ions from the surface. Calculations show that the energy barrier across which calcium ion precipitation occurs is not very high and is relatively easy to achieve. Calcium ion precipitation leads to the formation of two calcium silicate water complexes, laying the foundation for the formation of hydrated calcium silicate. The study provides a guidance for design the sustainable building materials at nano scale.
Chloride (Cl) induced steel corrosion is a major cause of durability issues of reinforced concrete (RC) structures and causes a large economic loss every year. Understanding the mechanisms of Cl induced steel corrosion in concrete is of great importance to develop the anti-corrosion methods and further lower down the repair and strengthening consumptions for sustainable development. Here, we investigate the mechanisms of steel depassivation and corrosion at atomic scale through the density functional theory (DFT) calculations. Our results reveal that Cl species can interact with the passive films through weakening the bonding of oxygen (O) with outer iron (Fe) atoms while enhancing the hybridization of O with inner Fe atoms, thus inducing the breakdown of passive films.
In terms of nanotechnology, this report describes how cement particles can be used to prepare 5 nm calcium hydroxide particles and to enhance the mechanical properties of organic materials, as well as to develop applications for related products. In addition, it also introduces how to use nanoparticles to modulate the nanostructure of cementitious materials to achieve the enhancement of macroscopic properties. These include the use of networks generated by the polymerization of organic monomers during hydration to improve the flexural strength of cementitious materials, the use of nano-silica to produce high modulus concrete, and the use of nano-foam to prepare high-quality lightweight cementitious materials. The report concludes with an outlook on the application of nanoscience and technology in civil engineering materials research to achieve sustainable development.

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Engineering nano silica aerogel from waste glass for lightweight insulating concrete

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Keywords: Nano silica aerogel; Cement hydration; Nucleation effect; Pozzolanic effect; Carbon sequestration

This study aims to prepare nano silica aerogel (NSA) derived from waste glass through a carbon dioxide (CO2) based extraction process. The synthesis of NSA was optimized by varying key reaction parameters such as extraction temperature, duration, NaOH concentration, and waste glass fineness. The resulting silicate precursors demonstrated good CO2 capture efficiency and highly porous NSA particles. The synthesized NSA showed an extremely high surface area and high porosity and can be used as a value-added lightweight reactive supplementary cementitious material for producing thermal insulating concrete. The incorporation of NSA accelerated the hydration by nucleation and pozzolanic effects. The nucleation effect contributed 21% of the 24-hour hydration, while the pozzolanic reaction effect only contributed 3%. The initial acceleration in hydration was attributed to the extremely high surface area of NSA, facilitating the precipitation of hydration products on its surface. At later stages of hydration, the pozzolanic reaction of NSA promoted the formation of C-S-H in the cement matrix. This reaction increased the chain length of the C-S-H gel, inducing a more robust and interconnected gel network. The densification effect mitigated the potential loss in mechanical properties caused by the presence of porous NSA. The porous structure of NSA significantly reduced the matrix density, leading to lower thermal conductivity and enhanced insulation properties. This study results offers a new pathway to valorize recycled glass, promote CO2 sequestration, and produce high-value aerogel, which can be used as a lightweight additive to develop lightweight insulating concrete.

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Evaluating Energy Absorption Capacity in Airtight Membranes for Sustainable Construction

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The mechanical performance of airtight membranes plays a critical role in sustainable construction, as these materials are essential for creating energy-efficient building envelopes that reduce energy losses and enhance durability. To achieve sustainability goals, construction materials must not only ensure airtightness but also withstand mechanical stresses such as wind loads, dynamic building movements, and temperature fluctuations. Tensile testing evaluates the ability of membranes to resist uniaxial forces, measuring parameters such as peak force, elongation, and energy absorption until failure. Additionally, tear testing evaluates the resistance of membranes to stress, assessing scenarios where small defects or punctures could lead to insufficient load application. These tests aim to provide a better understanding of the mechanical resilience of membranes, focusing on their ability to dissipate energy and maintain performance under real-world conditions. This study specifically focuses on airtight membranes designed to comply with the latest building standards, addressing energy efficiency and sustainability objectives while supporting reduced carbon emissions. While tensile and tear resistance of membranes have been widely studied, the concept of Energy Absorption Capacity (EAC) remains underexplored. EAC provides a holistic measure of a material's ability to dissipate mechanical energy, contributing to its resilience under dynamic loading. This study introduces a novel approach by comparing EAC values derived from tensile and tear tests across four different airtight membrane products, offering new insights into their suitability for sustainable construction applications.

The methodology employed standardised tensile and tear testing (EN 12311-1 modified by EN 13859-1:2010 Annex A for the tensile test and EN 12310-1 for the tear test.) under controlled laboratory conditions to evaluate the mechanical properties of airtight membranes. Tensile tests involved applying longitudinal stress to membrane samples, measuring key parameters such as peak force, elongation at break, and energy absorption up to the point of failure. On the other hand, tear tests evaluated the membranes' resistance to tearing by using a nail shank and comparing durability of their performance under mechanical stress. Both tests were designed to reflect the performance demands of modern building standards, ensuring that the evaluated membranes can contribute to energy efficiency and durability while supporting reduced carbon emissions. Testing was repeated five times based on the standard for each membrane product to ensure statistical accuracy, reliability, and alignment with quality benchmarks for high-performance building materials. The tests were conducted using a ZWICK testing machine with a load capacity range of 0.5 kN to 5 kN, ensuring precise measurement of the mechanical properties of the membranes. Data analysis involved calculating Energy Absorption Capacity (EAC) as the area under the force-displacement curves obtained from both tests, providing a quantitative measure of each membrane's ability to dissipate mechanical energy. Calculating EAC through both tensile and tear testing is essential to comprehensively evaluate material performance under varying mechanical stresses, ensuring the selection of robust membranes for sustainable construction. High EAC values indicate greater material resilience, which translates into improved performance under dynamic and localised mechanical loads, essential for ensuring

durability and energy efficiency in sustainable construction applications. The results indicate variations in Energy Absorption Capacity (EAC) across the tested membranes, reflecting differences in their mechanical performance under tensile and tear stress conditions. These findings highlight the importance of assessing both tensile and tear properties to gain a comprehensive understanding of membrane behaviour. This approach supports informed material selection for sustainable construction applications, where mechanical resilience and durability are critical for ensuring long-term performance. The findings emphasize the importance of EAC analysis in identifying membranes with optimal energy dissipation and stress resistance, ensuring their reliability in maintaining airtightness and energy performance over time. This approach supports innovative material selection for sustainable construction, where durability under mechanical stress directly contributes to building longevity and resource efficiency.

Keywords: Energy absorption capacity, Sustainable construction, Mechanical performance, Membrane testing methodology, Building envelope durability

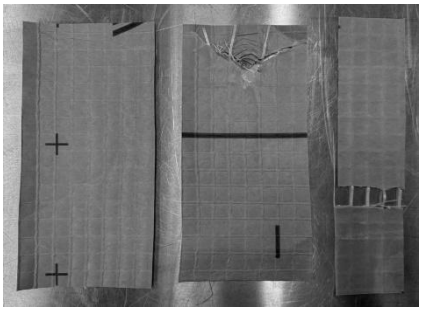

Figure 1. Membrane specimens before and after tear and tensile tests under the mechanical stress effects.

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Evaluation of lifetime of the asphalt mix, including the RAP processed using an splitting method

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Keywords: processing and splitting of RAP, binder-rich fine fraction, asphalt mortar, lifetime calculation, rotor centrifugal crusher

Abstract: Reclaimed asphalt pavement (RAP) is reused in Germany in accordance with the Circular Economy Act (KrWG, 2012). The aim is to maximize the reuse rate and the target must be to reuse 100 % of the RAP for the production of asphalt mix.

The conventional preparation technology for RAP used in Germany is the crushing and screening of the RAP obtained by milling or crushing [TL AG-StB 09, 2009]. The RAP material after preparing with this method shows mostly grain refinement and inhomogeneity in the composition of different fractions and binder content. These lead to limitation in the dosage rate of the RAP, that can be reused, because the performance and mechanical properties of asphalt with inadequate fines content and heterogeneity material composition can significantly be impacted. Consequently, innovative methods must be found to increase the quantities of RAP added.

This paper focus on extended evaluation of the asphalt mix including the RAP prepared using an innovative method (rotor centrifugal crusher (RCC-RAP)) to process the RAP. The influence on the lifetime of the asphalt mix with RCC-RAP content in comparison to the conventional method has yet to be fully investigated. As part of the research project, the influence of differently prepared RAP on the lifetime of the asphalt mixture produced with RAP were investigated. However, it is important that asphalt mixes containing RCC-RAP should perform similarly or better than asphalt mixes with conventional prepared RAP.

RCC-RAP preparing method is a grains friendly compared to the conventional preparation technology: crushing and granulations of the RAP. By use of this innovative preparing method "Splitting", the RAP can be splitted into a binder-rich fine fraction (asphalt mortar) and binder-poor coarse fraction. The processed RAP material can be sieved into different fraction and can be used to produce an asphalt mix exactly according the job mix design. The coarse aggregates with a poor bitumen content can be considered like virgin aggregates and added through the white drum. The asphalt mortar with high bitumen content can be added as usual in the mixer or with heated aggregates.

The finding presented in this paper is part of an ongoing investigation and this paper addressed an extended and comparative evaluation of the asphalt mix using analytical pavement calculation method, which were carried out with the performance and mechanical parameters of the individual asphalt variants. The extended evaluation includes the calculation of the service life of a heavy-duty asphalt pavement in

accordance with German analytical pavement design guide [RDO Asphalt 09/24] as well as an extended verification of the asphalt surface course and asphalt binder course with regard to fatigue resistance.

Based on the test results of the temperature-dependent stiffness modulus, fatigue resistance and low temperature behaviour, it was demonstrated that there are no significant differences between the asphalt mixture variants containing RAP produced by different methods (conventional and rotor centrifugal crusher) in terms of mechanical characteristics (temperature-dependent stiffness) and performance behaviour (fatigue properties). The determined test results show, both the quantity added and the optimization of target grading curve of the asphalt mix can be improved without to affect the performance properties of asphalt, when using reclaimed asphalts prepared by means of rotor centrifugal crusher.

The non-significant differences in terms of stiffness and fatigue behaviour as well as cold behaviour that had already been identified in the laboratory tests were confirmed by the pavement design calculations and the extended verification of the asphalt surface course and asphalt binder course. Minor differences in the results of these prognosis calculations cannot be clearly attributed to the preparation method here either. Thus, no concerns arise regarding the preparation method based solely on the determined lifetime.

However, the pavement with both conventional and rotor centrifugal crusher-processed RAP in the asphalt mixes fulfils the requirement of design criterium ≤ 100 % for the calculated fatigue status of a highly loaded asphalt pavement for a load cycle of 100 Mio. 10 t-ESAL (Bk100 of RStO 12/24) during a lifetime of 30 years.

By using this processing method, the reuse rate of RAP can be improved with conventional equipment of the asphalt mixing plants and a parallel drum is not necessary. The increase in the quantities of RAP added improve of resource efficiency and decarbonization (reduction of CO2 emissions).

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Examining the effects of environmentally friendly surface coatings on the corrosion-related mechanical characteristics of copper, aluminum, and carbon steel.

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Keywords: corrosion test; electrochemical test; weight loss test; environmentally friendly coating; mechanical properties.

This study explores the impact of corrosion on the mechanical properties of materials coated with an environmentally friendly substance. The research aims to evaluate the effectiveness of this coating in maintaining the structural integrity of metals used in various applications. The study uses various corrosion tests, including linear sweep voltammetry, open circuit potential measurement, and electrochemical impedance spectroscopy, to evaluate the corrosion resistance of the coated and uncoated samples. Tensile tests are also used to evaluate the mechanical qualities of the materials after exposure to corrosive conditions. The research focuses on carbon steel, copper, and aluminum, which are popular in sectors like construction, automotive, and electronics. The study found that the coating effectively prevents metals from corroding, with the coated aluminum sample showing a larger radius and higher resistance values than the untreated aluminum. The tensile strength of copper was also found to be better than the untreated aluminum. The study provides new insights into the complex interplay between mechanical qualities and corrosion resistance in materials protected by environmentally friendly coatings, which is crucial for industries seeking robust and sustainable solutions for various applications. Further research is recommended to fully understand aluminum behavior in corrosive environments and optimize the coating's performance in various situations.

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Experimental Investigation of Flexural Behavior in Carbon Grid-Reinforced Concrete Slabs

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Keywords: Carbon grid, Reinforced concrete, Flexural performance, Reinforcement ratio, Stiffness

Fiber-reinforced polymer (FRP) reinforcements, including glass-FRP (GFRP), carbon-FRP (CFRP), and aramid-FRP (AFRP), are increasingly used in infrastructure applications due to their superior corrosion resistance in extreme environments such as de-icing exposure and marine conditions. Among these, carbon grid reinforcements offer a durable alternative to conventional steel reinforcement. This study evaluates the flexural strength, deflection characteristics, stiffness properties, crack behavior, and failure mechanisms of carbon grid-reinforced concrete slabs with varying reinforcement ratios and configurations.

A total of 13 full-scale slab specimens were fabricated, consisting of two reinforced concrete (RC) slabs and 11 carbon grid-reinforced slabs. Each specimen measured 3,000 mm × 1,000 mm × 120 mm. The carbon grid reinforcement had a tensile strength of 2,837 MPa and an elastic modulus of 150 GPa, while SD400-grade steel and 30 MPa concrete were used for comparison. The slabs were subjected to four-point bending tests using a 3,000 kN universal testing machine (UTM) to assess flexural performance. Displacement transducers (LVDTs) were installed to measure slab deflections, while load, displacement, and reinforcement strain data were continuously recorded.

The experimental results showed that carbon grid-reinforced slabs developed 4–5 cracks in the constant moment region, with minimal differences in crack distribution between reinforcement types. However, unlike steel reinforcement, carbon grids lacked plastic deformation, leading to elastic failure. Some specimens experienced brittle failure upon reaching the ultimate load, with a sudden loss of strength. In contrast, RC slabs exhibited ductile behavior, with increased deformation after yielding. Carbon grid-reinforced slabs showed an initial stiffness reduction after cracking but maintained stable stiffness until ultimate load failure, followed by a sharp decrease in strength.

Deflection at peak load varied with reinforcement configuration. For slabs with a carbon grid width of 10 mm, increasing the number of layers led to a deflection increase from 85 mm to over 110 mm. However, when the grid width was 20 mm, additional layers had no significant effect on deflection. The flexural capacity was proportional to the reinforcement ratio. At a reinforcement ratio of 0.20%, specimens with two reinforcement layers exhibited the highest stiffness. When a single layer was used, specimens with increased reinforcement thickness showed higher stiffness than those with increased width. A similar trend was observed at a 0.40% reinforcement ratio. However, at 0.60%, specimens with three layers showed a slight decrease in stiffness when thickness increased, indicating the need for further study on the effects of reinforcement layering.

The elastic modulus of conventional CFRP reinforcement is approximately 100 GPa, whereas the carbon grid in this study had an elastic modulus of 150 GPa, which is 25% lower than that of steel reinforcement. Designing solely based on reinforcement strength may lead to excessive deflection in flexural members. To address this, a stiffness coefficient (K) was introduced:

$$K = E_r A_r d^2$$

where E_r is the elastic modulus, A_r is the reinforcement cross-sectional area, and d is the effective depth of the slab.

Carbon grid-reinforced slabs with K-values between 0.45 and 0.60 exhibited stiffness comparable to or higher than RC-1 (K = 0.51) after cracking. As the K-value increased from 0.60 to 1.20, slab stiffness also increased, with K = 0.90 showing similar characteristics to RC-2 (K = 1.00). These results suggest that incorporating the stiffness coefficient into serviceability design is essential.

Load-strain analysis indicated that steel reinforcement in RC slabs exhibited plastic deformation after yielding, while carbon grid-reinforced slabs maintained linear strain growth within the elastic range until failure. When multiple carbon grid layers were used, strain distribution followed a top-to-bottom gradient, with the outermost layer experiencing the highest strain. However, due to minimal depth differences between layers (approximately 3–5 mm), significant variations in strain were not observed. Given the inherently low stiffness of carbon grids, maintaining a uniform depth across the slab proved difficult, suggesting that reinforcement layering may not critically affect failure progression.

This study highlights the potential of carbon grid-reinforced concrete slabs as a durable alternative to steel-reinforced slabs. The findings indicate that stiffness and strength depend on reinforcement ratio, grid thickness, and layering. The introduction of the stiffness coefficient (K) provides a practical parameter for controlling deflection and ensuring serviceability. Further research is recommended to refine design methodologies for optimizing carbon grid-reinforced flexural members.

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Findings and Insights from Condition Assessment of 50-year RC Building in Composite Environment

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Keywords: Carbonation, Corrosion rate, Half-cell potential, Moisture, Durability

Amidst the increasing demand for the adoption of new low-clinker cements and growing concerns regarding their performance in carbonation and carbonation-induced corrosion, the authors present intriguing findings and insights from the condition assessment of a reinforced concrete building erected in the early 1970s located in a composite environmental zone of India. Structure in such an environment is deemed most susceptible to carbonation-induced corrosion. Despite the use of Ordinary Portland Cement (OPC) in its construction, the study enabled the identification of potential areas susceptible to carbonation and corrosion within the structure. These findings are relevant for evaluating the performance of new binders as well. After preliminary inspection, the locations for the secondary testing on the primary structural members were identified. The study incorporates a combination of semi-destructive and non-destructive, encompassing core sampling, carbonation depth analysis, half-cell potential measurement, corrosion rate assessment, and surface resistivity testing. The electrochemical/corrosion rate-related tests were performed in situ on different members after saturation of the concrete cover.

The investigation revealed considerable variation in carbonation depth across different test locations, underscoring the importance of considering varying carbon dioxide concentrations for accurate service life estimation in residential and commercial buildings. Members adjacent to the kitchen area had the highest carbonation depth, followed by the living area members, and members adjacent to the washroom area were characterized with the lowest carbonation depth. Additionally, the study uncovered that areas highly susceptible to carbonation may not necessarily exhibit correspondingly high corrosion rates. The member near the washroom, which showed crack signs, had the highest corrosion rate and most negative half-cell potential. In contrast, members in a similar environment with no cracks had a corrosion rate of 30.5 μm/year. It reaffirmed that the deterioration rate increases considerably once cracks reach the surface. Furthermore, a considerably high corrosion rate was observed in the kitchen member, which was found to be owning to the low-cover depth of the particular member, as other members in similar environments had no signs of aggressive corrosion. Living region spaces where the relative humidity is often controlled between 40 to 60% due to comfort and health regions. At such conditions, the corrosion rate is low, which was seen in the present study as the corrosion rate of members in living space was least, i.e., 2.9 μm/year. Lastly, by integrating surface resistivity, half-cell potential, and corrosion rate measurements, the study demonstrated the circumstances under which visual inspection of rebars becomes imperative and unavoidable, i.e., half cell-potential between -200 to -350 mV and surface resistivity between 15 to 40 kΩ-cm.

The present study's findings highlight that carbonation is necessary for initiation but not for dictating the propagation rate. Carbonation of the structure does not lead to widespread corrosion throughout the structural members in the building, as often believed. Corrosion is localized to specific regions characterized by moisture, i.e., frequent wetting and drying due to rain, continuous moisture near the washroom or kitchen plumbing, and damp regions. Members or regions with inadequate cover depth can also lead to aggressive corrosion conditions. For future low-clinker blend compositions, protection measures can be focused on highlighted regions to limit the corrosion activity in the structure.

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Gradient Designed Carbon Fiber Cement Composites with Absorption-Dominated Electromagnetic Interference Shielding

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Keywords: Absorption-dominated electromagnetic shielding; Gradient structure; Impedance match; Carbon fiber cement composites

Abstract: Cement, the predominant construction cementitious material, offers proven durability and scalability but critically lacks dielectric and magnetic loss capabilities, severely limiting its ability to absorb or shield electromagnetic (EM) waves. This inherent limitation renders traditional cement incompatible with modern architectural demands for EM protection in increasingly complex electromagnetic environments. Current EM protection strategies for buildings predominantly employ a metal backplane absorption model based on transmission line theory, wherein a reflective metal plate is integrated behind cementitious layers. However, this configuration fundamentally conflicts with practical architectural requirements. Effective EM-protective buildings must prioritize absorption-dominated shielding to dissipate incident waves within structures, thereby avoiding secondary EM pollution caused by reflection-based shielding methods. This critical distinction underscores the urgent need for a fundamental redesign of EM protection strategies for construction materials.

Carbon fiber is commonly incorporated into cement-based EM shielding materials primarily for reflection-based shielding due to its high electrical conductivity. In this study, three different lengths of chopped carbon fibers (0.5 mm, 1 mm, and 3 mm) were used as functional fillers and added to cement matrices at varying weight fractions (1 wt%, 2 wt%, 3 wt%, and 4 wt%) to construct an EM parameter library for carbon fiber cement-based materials. Based on multilayer impedance matching theory, the electromagnetic parameters and thicknesses of the multilayer structures were optimized by integrating genetic algorithms with EM simulations. A three-layer carbon fiber cement-based electromagnetic shielding material with full X-band absorptivity (A) ≥ 90% was successfully designed. Electromagnetic parameter testing revealed that increasing both the length and content of chopped carbon fibers led to higher real and imaginary parts of the complex dielectric constant, attributed to the formation of interconnected conductive networks. Conductivity testing corroborated this trend, with electrical conductivity increasing from 7.42×10^{-4} S/m (1 wt%) to 3.61×10^{-3} S/m (4 wt%). Additionally, single-layer samples exhibited reflection-dominated behavior (average reflectivity (R) > 50%), confirming their limited absorption capacity and potential for secondary EM pollution. The optimized three-layer gradient structure, composed of CF0501, CF0504, and CF1004 layers with thicknesses of 2.6 mm, 2.8 mm, and 3.7 mm respectively, achieved ≥ 90% absorption of EM wave energy across the entire X-band, with R values less than 10% and total shielding effectiveness (SET) ranging from 37.8 dB to 62.2 dB. Layered casting of these materials yielded actual SET values between 28.6 dB and 61.6 dB, A values from 0.58 to 0.76, and R values from 0.24 to 0.41, closely aligning with simulation outcomes. Notably, the EM shielding mechanism was absorption-dominated, in stark contrast to conventional reflection-based systems. Impedance analysis revealed a descending gradient in equivalent impedance across layers, facilitating progressive EM wave penetration. All three layers contributed synergistically to attenuation, diverging from the traditional "impedance-absorption-reflection" model. Microwave attenuation constants confirmed active energy dissipation within each layer, maximizing

overall shielding efficiency. This design eliminates reliance on reflective backplates, addressing both performance limitations and practical incompatibilities in architectural EM shielding applications.

In summary, this study demonstrates that tailored multilayer carbon fiber cement composites can achieve absorption-dominated EM shielding through controlled impedance gradients and optimization of conductive networks, offering a scalable and high-performance solution for electromagnetic protection in modern construction.

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Harnessing of Silica Sand into Ultra-high-Performance Concrete for Marin Mega Projects

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Keywords: silica-fume; concrete; marin structures.

The production of ultra-high-performance concrete (UHPC) requires a significant volume of silica fume, counting around 40% by weight of cement. The high amount of silica fume can hinder the use of UHPC due to the high cost. This paper investigates the possibility of developing sustainable ultra-high-performance concrete by partially replacing silica fume with readily available silica sand; namely, dune sand available in Saudi Arabia. Comprehensive engineering properties were evaluated; including (but not limited) chloride diffusion, carbonation depth, viscosity, porosity and mechanical strength. The produced UHPC achieved 4x higher compressive and tensile strength coupled with about 80x lower diffusion and carbonation depth. The major findings of this study confirm the feasibility of local silica sand to produce UHPC, meeting the required performance while promoting circular economy in the concrete industry.

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Impact of Freeze-Thaw Cycles on Water Mobility of Building Envelope Materials

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Keywords: Nuclear Magnetic Resonance, Relaxation Time, Building Envelope Materials, Freeze-Thaw.

Moisture accumulation and frost formation in porous building materials are critical factors influencing their durability, particularly in colder climates such as Canada, where frequent freeze-thaw cycles accelerate material degradation. When high moisture levels coincide with freeze-thaw cycling, the risk of frost damage increases significantly due to the physical action of freeze-thaw, which results from the 9% expansion of water when it freezes. This risk is further exacerbated by rapid freezing, which restricts moisture redistribution within the material and can lead to crack formation. The pore structure of a material plays a crucial role in its freeze-thaw resistance. However, repeated freeze-thaw cycles can also alter the pore structure, impacting various material properties. These changes can affect thermal performance, moisture response (e.g., moisture/water absorption-desorption), and even susceptibility to mould growth. One of the most robust techniques for characterizing changes in the complex pore structure of building materials is ^{1}H nuclear magnetic resonance (NMR) relaxometry. This method excites hydrogen nuclei in water, which act as sub-atomic magnets responding to an applied external magnetic field. Upon excitation, these nuclei undergo precession before gradually losing their coherence through relaxation. The dominant relaxation mechanism is the interaction between excited hydrogen nuclei and the pore surface. According to the fast exchange model, the transverse relaxation time (T_2) is inversely proportional to the surface-to-volume ratio (S/V) of the pores. This means that in smaller pores, where the S/V ratio is higher, hydrogen nuclei relax more quickly, resulting in shorter relaxation times. Conversely, in larger pores with a lower S/V ratio, relaxation occurs more slowly, leading to longer relaxation times.

The current study examined five different building materials, each tested in triplicate with dimensions of 2 × 2 × 0.5 inches at the Materials Durability Laboratory of the National Research Council of Canada. The selected materials include four commonly used in Canadian building envelopes: gypsum board, oriented strand board (OSB), plywood, and pine wood. Additionally, hempcrete, an emerging bio-based material that has gained significant attention in recent years, was investigated. Each material was subjected to two types of freeze-thaw cycling: freeze-thaw cycles under high relative humidity and wet freeze-thaw cycles following ISO 16987, with a total of 30 samples tested. Changes in the pore structure for all 5 sample types were analyzed using a single-sided ^{1}H nuclear magnetic resonance (SS-NMR) device. By employing the novel SS-NMR non-destructive testing method, pore structure modifications was characterized at different depths in each sample, providing valuable insights into the material's response to freeze-thaw exposure across various depth slices. In addition, changes in the weight and dimensions were recorded to monitor moisture build-up and any expansion.

The impact of freeze-thaw cycles on pore structure varied depending on the material type, with the most significant changes observed in materials with higher hygroscopic properties, as these materials provide more absorption sites for water during the freeze-thaw process. Under high relative humidity freeze-thaw conditions, plywood, OSB, and pine exhibited the highest water mobility, with their major peaks appearing at approximately 1 ms. In contrast, hempcrete and gypsum board showed no significant changes in water mobility, maintaining their major T_2 peaks below 0.2 ms. Freeze-thaw cycles primarily induced two key changes: (1) increased moisture accumulation within the material during thawing and (2) expansion of the

pore structure, leading to the formation of larger pores. This pore structure modification was not necessarily visible at the macroscopic scale and did not always result in cracking. However, they were reflected in the increased water mobility observed in aged samples compared to their initial state, especially in plywood, OSB, and pine. In conclusion, materials subjected to freeze-thaw cycles may become more susceptible to increased water mobility within the structure, which in turn can increase microbial activity and the risk of mould formation.

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Influence of Stacking Sequence of Flax/Glass Hybrid Laminates on Impact Energy Absorption at High Strain Rate

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Keywords: hybrid composite, SHPB, flax FRP, glass FRP, impact energy absorption.

Introduction

Due to excellent stiffness and strength, fibre-reinforced polymer (FRP) composites have been increasingly employed in many industrial sectors, including the building industry. Structures may be exposed to specific high-speed loadings, such as collisions, blasts, ballistic impacts, or the impact from runaway debris. Integrating FRP composites into structures can effectively increase their strength and reduce fragmentation, providing a significant improvement in the durability of the structures when subjected to the extreme loading conditions mentioned above. Taking into account the current security situation in Europe, the protection of structures from specific high-strain rate loading emerged as a critical concern. FRP composites offer an effective and lightweight solution—weighing up to 75% less than traditional steel—that can significantly contribute to the safety enhancement of building structures; however, to fully utilize their potential, a deep understanding of their behaviour under high strain rate conditions is crucial [1]. One of the most effective ways to achieve desirable properties in laminated composites is hybridization [2]. Hybrid flax/glass fibre-reinforced polymer composites have emerged as sustainable alternatives for impact-resistant applications. Current studies reveal that stacking sequences critically influence the properties of hybrid FRPs, such as interlaminar stress distribution and failure modes. While quasi-static properties of such hybrids are well-documented, their dynamic response at strain rates exceeding 1000 s^{-1} remains underexplored. The presented study addresses the knowledge gap by systematically investigating how flax/glass hybrid stacking sequences govern energy absorption at ultrahigh strain rates of about 2000 s^{-1}.

Methodology

Slab specimens (8 mm thickness) were manufactured by press moulding using epoxy-based adhesive. Cylindrical specimens with a diameter of 15 mm were then cut from the plates. Six configurations have been tested, the composition of the test specimen layers was as follows: (G-glasss, F-flax, numerical value - number of fabric layers)

1. F10G20
2. G10F10G10
3. G20F10
4. F15G15 (impacted from both sides)
5. G30

Stacking sequence is depicted in Fig. 1.

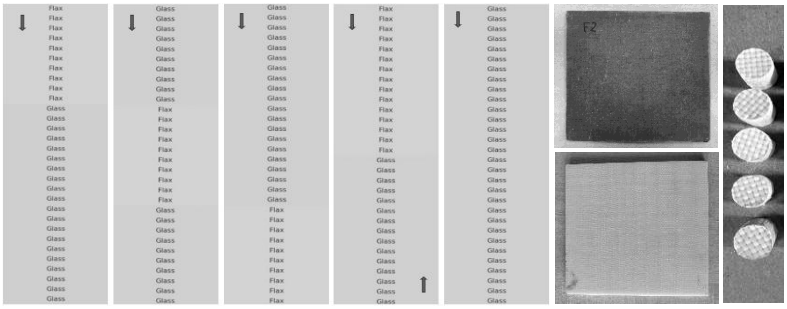

Figure 1. Stacking sequence and load direction of tested samples (left), example of laminate slabs (middle) and samples for SHPB tests

The energy attenuation of specimens at a high-strain rate of about 2000 s-1 was characterized using the Split-Hopkinson pressure bar (SHPB) method. Specimens were placed between an incident and a transmitter bar. A striker impacted the incident bar, generating a compressive stress pulse. Part of the wave was reflected, and part was transmitted through the specimen. Strain gauges fixed to the bars recorded the waveforms, allowing calculation of stress, strain rate, and absorbed energy. The relative attenuation, indicating energy dissipation, was determined from incident, reflected, and transmitted pulse amplitudes. The higher the relative attenuation value, the higher the shock wave energy absorption potential of the material can be predicted.

Results and discussion

The experimental results of high-strain rate testing using a Split-Hopkinson pressure bar (SHPB) are presented in Table 1.

Table 1. Characteristics of hybrid laminates

Material name	Plastic Strain [%]	Absorption relative [%]	Standard deviation [%]	Bulk density [kg/m3]	Thickness
F10G20	0.74	42.9	3.2	1730	8.0
G10F10G10	0.79	43.1	4.1	1730	8.1
G20F10	0.83	40.7	1.0	1730	8.05
F15G15_F	0.98	45.1	2.1	1625	8.1
F15G15_G	0.95	43.2	3.2	1625	8.0
G30	0.62	37.2	2.9	1950	8.15

The presented results confirm the advantageous effect of hybridization with flax fibres for energy absorption applications. All hybrid configurations showed higher energy absorption capabilities compared to the non-hybrid glass composite, with improvements ranging from 8.6% to 17.5%, which was similarly observed by Safri [3]. This enhancement can be attributed to the inherent damping properties of flax fibres. When comparing samples with the same fibre volume fractions but different stacking arrangements, differences in performance can be observed. The higher performance of the F15G15_F configuration (45.1% absorption) compared to F15G15_G (43.2%) suggests that the sequencing of the impact side plays a role in energy dissipation mechanisms. This finding aligns with research by Cheour et al [4]. When impact occurs on the flax side, the natural fibres provide initial energy dissipation through their damping characteristics before the more rigid glass layers engage in the energy absorption process [5]. In the series of samples with 2/3 glass content, the influence of the position of the layers on the energy absorption is also evident. In this set, as in the previous case, sample F10G20 with flax layer impact side showed higher energy absorption values compared to sample G20F10 (glass layer impact side). Sample G10F10G10 with a flax layer in the middle position showed the highest energy absorption rate within the set (43.1% compared to 42.9 and 40.7). The higher number of interfaces of different materials also contributes to the final value

of energy absorption [5]; when an impact wave encounters an interface between materials with different acoustic properties (e.g., flax and glass fibres), part of the wave reflects, and part refracts. This phenomenon creates multiple reflections and refractions, which gradually reduce the intensity of the wave.

Conclusions

- Replacement of part of the glass layers in the laminate by flax increases the energy absorption efficiency of the composites at high strain rates. Hybrid composites consistently showed 8.6–17.5% higher energy absorption compared to pure glass laminates.

- Hybridization also enabled significant weight reduction (up to 17% compared to pure glass) while maintaining or exceeding energy absorption values.

- The position of the flax layers in the laminate affects its ability to absorb impact energy. The most effective solutions are layers of flax fibres placed on the impact side or in the core.

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Influence of Steel Fiber Connectivity on the Thermal Conductivity of Steel Fiber-Reinforced Cementitious Composites: An Experimental and Numerical Investigation

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Keywords: Steel fiber-reinforced cementitious composites, Thermal conductivity, Connectivity, Orthogonal experiment, Finite element simulation

Thermal management in modern building structures is a critical challenge that directly influences energy efficiency and the durability of constructions. Cementitious composites, which form the backbone of many infrastructures, play a central role in both insulation and heat transfer. Despite significant advances in using lightweight aggregates and thermally conductive fillers to modify the thermal properties of concrete, achieving a high degree of thermal conductivity while maintaining mechanical integrity remains elusive. Recently, steel fiber reinforcement has emerged as a promising approach to enhance the thermal performance of cement-based composites. However, the effectiveness of this method largely depends on the connectivity of the fibers within the matrix—a factor that is influenced by the fiber volume fraction, length-to-diameter (L/D) ratio, and the water-to-cement (w/c) ratio. This study focuses on the pivotal role of steel fiber connectivity in enhancing the thermal performance of steel fiber-reinforced cementitious composites (SFRCC) and establishes a quantitative relationship between steel fiber connectivity and composite thermal conductivity.

To achieve this objective, orthogonal experiments, range analysis, and ANOVA confirm were employed to comprehensively evaluate the effects of steel fiber L/D ratio, volume fraction, and w/c ratio on the thermal conductivity of SFRCC. Our analysis confirmed that the steel fiber volume fraction has a statistically significant impact on the experimental metrics. Mortar specimens were prepared in $40 \times 40 \times 40$ mm³ molds, with each formulation maintaining a constant w/c ratio of 0.45 and a fixed steel fiber L/D ratio of 25 across varying fiber volume fractions. After 28 days of curing, thermal conductivity was measured using a DRE-III multifunctional rapid thermal conductivity tester. In addition, Y.CT PRECISION S X-ray computed tomography scanner was employed to assess connectivity of the steel fibers within the matrix.

In parallel with the experimental investigations, a finite element (FE) simulation was conducted to model the thermal behavior of SFRCC under three-dimensional porous conditions across various fiber volume fractions. In this FE model, the thermal conductivities of the cementitious matrix and steel fibers were set at 1.8 W/m·K and 50 W/m·K, respectively, which are representative values reported in the literature. The simulation was designed to elucidate the impact of fiber connectivity on the effective thermal conductivity of the composite. Furthermore, a refined connectivity–thermal conductivity model was developed to establish a quantitative relationship between fiber connectivity and the overall thermal performance.

Results indicate that an optimal steel fiber volume fraction of approximately 3.5% yields the maximum thermal conductivity in SFRCC. Within the 0.25%–3.5% range, both experimental and FE-simulated

thermal conductivity values increase with higher fiber content. However, beyond 3.5%, the trend levels off, and further increases in fiber content may even reduce thermal performance due to fiber clustering, which diminishes effective connectivity. Microstructural analyses corroborate these observations by revealing that well-dispersed and interconnected fibers form continuous conductive pathways that significantly lower thermal resistance, whereas non-uniform fiber distributions result in isolated clusters that cannot establish efficient heat transfer networks.

The refined model indicates that both the connectivity and volume fraction of steel fibers are critical for enhancing heat conduction. Even slight variations in fiber interconnection can significantly impact the overall thermal performance of the composite. These findings underscore the importance of optimizing fiber dispersion and connectivity—not only to boost thermal conductivity but also to maintain the mechanical integrity of the composite.

In summary, this study demonstrates that steel fiber connectivity is the key determinant of SFRCC thermal performance, with an optimal fiber volume fraction of approximately 3.5% that simultaneously enhances both thermal conductivity and mechanical properties. The integration of experimental data, finite element simulations, and refined analytical models provides a robust framework for understanding the interplay between microstructural connectivity and heat transfer. These insights offer valuable guidance for the design and optimization of advanced cementitious composites tailored for high-performance thermal management applications.

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Influence of Two-Stage Mixing Approach on Strength and Shrinkage Properties of Recycled Concrete Aggregate-Based 3D Printable Mortar

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Keywords: TSMA, Recycled Concrete Aggregates, Shrinkage, 3D concrete printing.

The rapid depletion of natural resources and the growing demand for use of good quality aggregates in concrete has necessitated the exploration of sustainable alternative aggregates. In this context, Recycled Concrete Aggregates (RCA) is emerging as one of the promising solutions to reduce the environmental impact of natural aggregates usage in concrete production. The extraction and processing of natural aggregates not only consume significant energy but also lead to habitat disruption and ecological imbalances. However, the use of RCA presents challenges due to the presence of surface defects like high porosity and cracks on adhered mortar, increases water absorption and lowers the concrete strength. Hence, the use of RCA in concrete is restricted generally to non-structural applications. In this regard, various surface treatment techniques, including silica fume slurry, cement slurry, and carbonation treatment, have been proposed to improve RCA properties by enhancing bonding and reducing water absorption. These methods work by densifying the surface of the RCA, reducing porosity, and creating a stronger ITZ. Among these methods, the Two-Stage Mixing Approach (TSMA) has gained attention for its potential to significantly improve the strength of recycled aggregate-based concrete compared to traditional mixing methods. During the first stage of mixing, TSMA uses half of the required water, forming a thin layer of cement slurry on the surface of RCA. This slurry permeates the porous old cement mortar, filling cracks and voids, thereby improving the mechanical properties of the recycled concretes aggregates. In the second stage, the remaining water is added to complete the mixing process, resulting in a well-integrated material. Although there is growing evidence that TSMA enhances strength, its influence on shrinkage properties, particularly in 3D printable concrete systems, remains largely unexplored. This is a critical consideration, especially for 3D concrete printing, where shrinkage behavior is more pronounced due to rapid curing and stress distribution during the printing process. Shrinkage control is essential for maintaining the dimensional stability of printed structures and ensuring their durability. This study investigates the influence of the Two-Stage Mixing Approach (TSMA) on the strength and shrinkage properties of 3D printable mortar incorporating 30% RCA as a partial replacement for natural aggregates. The mortar mix is designed with a water-to-binder ratio (w/b) of 0.4. The study compares the performance of two mixing methods: the conventional Normal Mixing Process (NMP), following ASTM C192, and the Two-Stage Mixing Approach (TSMA). The aim is to assess the impact of these mixing techniques on the mechanical properties, such as compressive and flexural strength, and shrinkage behavior of the mortar, particularly in the context of 3D printing applications. The study will measure autogenous shrinkage, both linear and volumetric, and drying shrinkage, for both cast and printed specimens. The results from this study are expected to provide valuable insights into balancing strength improvement and managing shrinkage, which is crucial for the performance and durability of 3D printed concrete. The findings will contribute to optimizing the use of TSMA in 3D printable mortar and offer guidance for developing more sustainable and efficient construction materials.

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Intelligent Perception and Decision-Making Technology for the Durability of Shield Tunnel Segments in High Water Pressure Erosion Environments

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Keywords: concrete, shield tunnel, erosion, durability

Underwater shield tunnels are typically situated in aquatic environments characterized by high humidity, elevated water pressure, and a high concentration of erosive ions. The reinforced concrete segmental lining of shield tunnels is continuously exposed to groundwater and soil conditions, making it highly susceptible to severe deterioration due to multiple environmental factors, including water infiltration, salt spray, and wet-dry cycles. The aggressive media present in the environment (e.g., Cl^-, SO_4^{2-}) exhibit strong penetrative capabilities into the pores and cracks of concrete, leading to concrete salinization and corrosion. This process results in the cracking, spalling, and peeling of the concrete protective layer, facilitating the sustained propagation of cracks. Consequently, the passivation film of the embedded steel reinforcement is disrupted, leading to reinforcement corrosion, expansion-induced cracking, and, ultimately, severe degradation of the mechanical performance of the tunnel lining structure. Moreover, as tunnel diameters and water pressures continue to increase, durability under high water pressure has become a critical challenge. The segmental lining subjected to high water pressure is simultaneously affected by chloride ion diffusion and convection. Within a certain range near the segment surface, convection often dominates the chloride transport process, making it a key factor influencing chloride penetration. As a result, the presence of high water pressure significantly accelerates chloride migration into the lining, exacerbating the corrosion and deterioration of reinforced concrete segments. Neglecting the effect of external water pressure may lead to insufficient durability during the service period, resulting in material degradation, structural damage, and water leakage, ultimately compromising the operational performance and service life of the facility. Additionally, the inner side of the tunnel segments is often directly exposed to a salt spray environment, which accelerates the corrosion of reinforcement and joint bolts, making these areas particularly prone to structural damage. Therefore, the durability of shield tunnel segmental linings presents numerous concerning issues, all of which pose long-term challenges to both structural durability and safety.

This study aimed to elucidate the deterioration mechanisms and processes of segmental linings under the coupled effects of external geotechnical loads, ionic erosion, and high-water-pressure environments, as well as internal corrosion factors such as salt spray and carbon dioxide. The research sought to uncover the damage evolution patterns of shield tunnel segmental structures under the combined effects of internal and external corrosive environments and establish a relationship model between the degradation state of the segment structure throughout its service life and the properties of its corrosion products.

A durability model was also developed to correlate rubber gasket performance with deformation/stress-ion concentration relationships. The impact of segment joint conditions and variations in bolt stress on the stress state of rubber gaskets was investigated to determine the aging patterns of the gasket material. Addressing the current limitations in durability monitoring technologies, which fail to accurately track the in-service condition of underwater concrete structures and consequently lead to delayed maintenance, this study designed and developed high-precision, anti-interference, low-latency sensors with long-term stability for monitoring concrete deterioration, reinforcement corrosion, and structural joint conditions.

By integrating multi-sensor in-situ dynamic monitoring and data fusion, a deep learning-based mathematical model was established. In parallel, an intelligent perception and deterioration early-warning decision-making system for the

durability of ultra-long cross-river tunnel structures was developed. This system provided timely information and scientific decision-making support for the restoration and enhancement of tunnel structural performance, ensuring the safe operation and maintenance of ultra-long cross-river tunnels.

Long-Term Durability of Textile-Reinforced Mortar in Acidic Environments: Influence of pH and Exposure Duration on Mechanical Performance

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Keywords: Please insert a maximum of 5 keywords.

Keywords: Textile reinforced mortar; TRM; Fiber Reinforced Cementitious Matrix; FRCM; Tensile testing; Mechanical properties.

Textile Reinforced Mortars (TRM) have emerged as a sustainable solution for strengthening existing masonry structures and are gaining significant popularity in contemporary construction practices. This system entails embedding textile fibers within an inorganic matrix, typically cement or lime-based mortars, and applying it over the surface of the substrate. While extensive research has been conducted on the mechanical properties of these composite systems, there remains a dearth of knowledge concerning their long-term performance and durability. Thus, the objective of the present study is to enhance our understanding in this field by investigating the bond behavior of TRM composites comprising basalt textiles and a lime-based mortar after exposure to acidic and alkaline attacks using a single lap shear test. To achieve this objective, a clay brick as the substrate has been employed, and constructed single-lap shear specimens using a lime-based mortar and a basalt fabric. These specimens were subjected to accelerated aging conditions simulating acidic and alkaline environments. The temperature and pH of the solutions were maintained at constant levels throughout the exposure period. Specifically, the specimens were tested after 1000, 3000, and 5000 hours of exposure to evaluate their bond behavior in comparison to control specimens of the same age. Furthermore, the effect of acidic and alkaline environments was investigated on the material properties of the constituent materials. Elastic modulus tests were also conducted on cylindrical mortar samples and compared against reference samples. Moreover, optical microscopy was utilized for a better understanding of the deterioration.
The results obtained from our study reveal compelling insights into the behavior of TRM composites over extended durations of exposure. As the exposure time increased, the mortar exhibited significant deterioration, leading to a notable change in the failure mode of the TRM composite. By identifying the strength, stiffness, and failure mode of each specimen and comparing them to the reference stage, it was possible to derive essential design parameters for various field applications. The findings of this research

contribute to the existing body of knowledge on TRM systems by shedding light on their long-term performance and durability under acidic and alkaline environments. The characterization of bond behavior and the identification of material property changes provide valuable information for engineers and practitioners involved in designing and applying TRM solutions for masonry structures. Understanding the behavior of TRM composites in chemical attacks is crucial for ensuring their reliable and effective implementation in real-world scenarios as well as an initial understanding of durability modeling.

Future research directions in this domain may include exploring additional environmental conditions, investigating the influence of different types of textile fibers, and evaluating the performance of TRM composites in varying temperature and moisture conditions. Such investigations will further enhance understanding of such a sustainable strengthening solutions and aid in the development of guidelines and design recommendations for their optimal utilization. Finally, each specimen's strength, stiffness, and failure mode have been identified and compared to the reference stage to derive design parameters for various field applications. These results showed the sensitivity and major reduction in the material properties of basalt-TRM over the acidic medium and draw a good understanding of its aging behavior and alteration of the failure mechanism.

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Machine Learning Model to Identify Steel Rebar Replacement Fibre Dosage

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Keywords: Concrete; fibres; rebar; machine learning.

Significant effort has been made in recent years to address the immense environmental impact of concrete. Given that cement production generates about 6% of all global greenhouse gas emissions, the focus has been heavily weighted toward reducing the clinker content of concrete. Reducing the clinker content can primarily be achieved through the development of novel cements to replace Portland cement, or though the use of mineral powders (pozzolanic, cementitious, or inert) to offset some portion of the Portland cement. However, regulatory approval of new cements – and the ramp up of new production facilities – is an arduous and lengthy process. And cement content optimization in concrete is reaching a limit such that additional significant reductions in Portland cement contents are not likely. With this reality in mind, it is worth noting that steel reinforcing bar ("rebar") production contributes about 1.5% of all global greenhouse gas emissions, indicating the potential for massive gains to be made using alternative reinforcement with lower carbon footprint, such as fibres. Fibre production, be it through manufacturing or recycling, offers the potential for lower embodied carbon when compared to rebar manufacturing. Furthermore, the use of fibres in certain structural elements can reduce the needed volume of concrete through reduced element size, leading to further reductions in embodied greenhouse gases.

Discrete fibre reinforcement has shown the ability to provide equivalent or better reinforcing capacity as rebar for certain applications. For instance, for slabs on grade such as pavements and floors, rebar is primarily used to control temperature and shrinkage effects and to provide post-cracking moment capacity. In the United States, a recently published American Concrete Institute (ACI) specification (ACI Spec-544.12.23) provides a design methodology that identifies residual flexural strength (as determined from ASTM C1609) of fibre reinforced concrete necessary to provide equivalent post crack moment capacity to a rebar reinforced slab as a function of rebar reinforcement ratio.

The ASTM C1609 flexural experiment requires specialized equipment that most concrete producers and contractors do not have. Furthermore, there are no viable models to predict the residual flexural strength of fibre reinforced concrete, given the complex, coupled, functional dependency on fibre dosage, fibre characteristics (material, diameter, length, shape, etc.), and concrete characteristics (w/cm, aggregate size and content, paste content, compressive strength, etc.). Although studies have been performed to evaluate the effect of individual parameters on flexural strength, to date there has not been a comprehensive evaluation to identify the coupled effects of fibre and concrete characteristics on the residual flexural strength of fibre reinforced concrete. This combination of the need for specialized testing equipment and lack of robust predictive models hinders more significant utilization of fibres to replace rebar for post-crack moment capacity in concrete slabs. To mitigate this roadblock to more widespread adoption of fibres, a machine learning based model was developed to identify functional dependencies of residual flexural strength on fibre and concrete characteristics, proportions, and properties. The model was trained and tested based on a combination of experiments and data mining for steel fibre reinforced concrete flexural

testing. Experiments focused on ASTM C1609, with several different concrete compositions and fibre dosages.

The primary outcome of the experiments, data mining, and the machine learning model was the ability to accurately predict the residual flexural strength of a range of concrete mixtures with a range of steel fibre dosages, steel fibre shapes, sizes, and aspect ratios. In combination with the new ACI specification, this model can serve as a design aid to specify minimum fibre dosages for different applications (particularly slabs on grade), different concrete mixtures, and different steel fibre sources.

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Mechanical Characterisation of Sustainable Lightweight Aggregate Foam Concrete for Non-Structural and Structural Applications

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Keywords: Lightweight aggregate foam concrete, Sintered fly ash porous aggregates, Foam, Sustainable construction material, Structural application.

Abstract

The growing demand for sustainable construction materials has led to the development of lightweight aggregate foam concrete (LAFC) as depicted in **Figure 15**. LAFC integrates the benefits of lightweight aggregate concrete (LWAC) and foam concrete (FC). This study investigates the mechanical properties of LAFC for non-structural and structural applications, focusing on compressive strength, tensile strength, flexural strength, and water absorption. It also compares the results with ASTM standard requirements to evaluate the suitability of LAFC for practical applications. The combination of sustainable sintered fly ash porous aggregates (SFA) with foamed concrete enables a significant reduction in density while maintaining sufficient structural strength and acoustic and sound insulation properties.

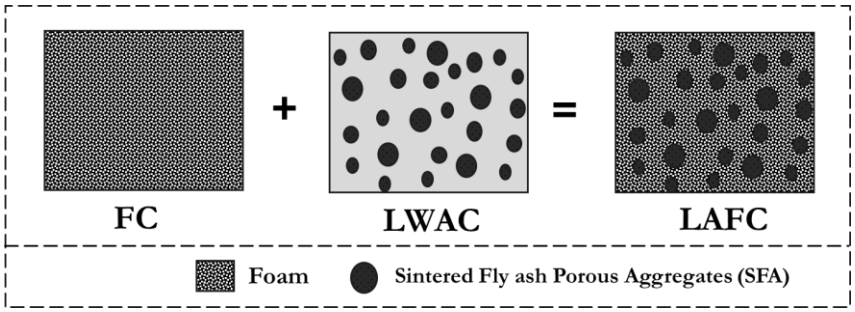

Figure 15. Concept of lightweight aggregate foam concrete (LAFC)

A comprehensive experimental program as shown in **Figure 16** was designed to assess the mechanical behavior of LAFC for densities of 1400 kg/m^3 and 1800 kg/m^3 by incorporating SFA into CFC. Additionally, minimal usage of cement and fly ash were used as a binder, promoting sustainable development in concrete production. A synthetic foaming agent Sodium lauryl sulfate (SLS), and foam stabilizers Xanthan and Sodium hydroxide are used to optimize the foam solution concentrations to generate stable foam with a controlled pore structure. The density of stable foam produced and used in this study is 50 kg/m^3. The mix proportions were designed to achieve 1400 kg/m^3 and 1800 kg/m^3 target densities, considering factors such as the foam content (30 % and 15%) and LWA replacement level.

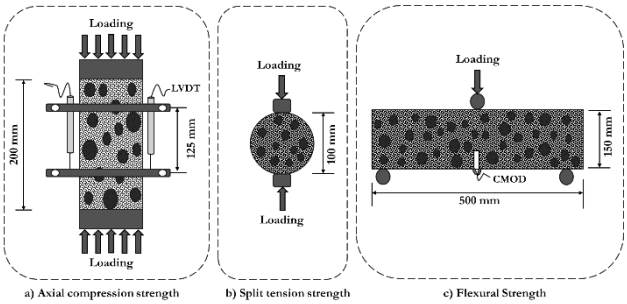

Figure 16. Experimental program

All mechanical properties of LAFC are directly related to achieved density, for considered both target densities the fresh state densities achieved within the allowable deviation of ± 50 kg/m³. The compressive strength of LAFC is evaluated using cube and cylinder specimens at 28 days curing age. Results indicated that the strength development of LAFC is influenced by the foam and proportion of LWAs, as well as the stability of the foam matrix. At a density of 1400 kg/m³, the cube and cylinder compressive strengths were 15 MPa and 13 MPa, respectively, while at 1800 kg/m³, they reached 30 MPa and 24 MPa. The inclusion of LWAs significantly enhanced compressive strength, meeting the requirements for structural concrete applications. However, compressive strength of LAFC is 25% lesser than the LWAC at same density for example 1800 kg/m³.

Tensile and flexural strengths of LAFC were evaluated using split tensile and three-point bending tests, respectively. The incorporation of LWAs enhanced fracture toughness and energy absorption capacity. The splitting tensile strength was found to be 16.26% and 9.53% of the compressive strength at densities of 1400 kg/m³ and 1800 kg/m³, respectively, aligning with conventional LWAC behavior. Additionally, flexural strength tests indicated that LAFC exhibits improved ductility compared to normal-weight concrete, attributed to the uniform distribution of air voids and enhanced interfacial bonding between the foam matrix and LWAs. The flexural strength was measured as 10.55% and 8.37% of the compressive strength at densities of 1400 kg/m³ and 1800 kg/m³, respectively. Basic durability performance was evaluated through a water absorption test. Due to the air void system present in LAFC, the water absorption was higher than in conventional concrete which is typically 3 to 5%. However, for densities 1400 kg/m³ and 1800 kg/m³, water absorption found 10 % and 8% respectively.

A comparative assessment shown in **Table 8** was conducted between experimental results and ASTM standards determine LAFC's suitability for structural applications. The results demonstrated that LAFC with densities 1400 kg/m³ and 1800 kg/m³ meets the strength requirements for non-load-bearing and certain load-bearing structural components, such as partition walls, precast panels, and lightweight floor slabs. The improved workability, ease of handling, and potential for prefabrication make LAFC a viable alternative to traditional concrete in sustainable construction.

Table 8. Comparative assessment of LAFC with ASTM specifications

Properties	Achieved Properties		ASTM Specification	
	Structural	Non-Structural	Structural	Non-Structural
Target Density (kg/m³)	1800	1400	1800	1400
Fresh State Density (kg/m3)	1811	1407	1800 ± 50	1400 ± 50

Cube Compressive Strength (MPa)	30	15	>17	< 17
Split tensile Strength (MPa)	2.86	2.44	>2.00	-
Water Absorption (% by mass)	8	10	3 to 10	10 to 25

The study highlights the potential of LAFC as a sustainable alternative for non-structural and structural applications. The experimental results demonstrate that LAFC, with densities of 1400 kg/m³ and 1800 kg/m³, achieves sufficient compressive, tensile, and flexural strengths while maintaining reduced density. The optimized use of synthetic foaming agents and stabilizers ensures stable foam formation, contributing to the mechanical performance and durability of LAFC. Overall, this study establishes LAFC as a promising material for sustainable construction, particularly in non-load-bearing and selective load-bearing applications, supporting the advancement of lightweight and energy-efficient concrete solutions.

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Mechanism of glass powder mitigating alkali-silica expansion of concrete: Synergy control of ion diffusion and adsorption

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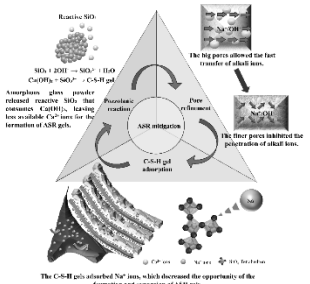
Email of the corresponding author:: jxinlu@polyu.edu.hk (Jian-Xin Lu), cecspoon@polyu.edu.hk (Chi Sun Poon)Abstract

The alkali-silica reaction (ASR), driven by reactive silicate dissolution and osmotic gel swelling, remains a critical degradation mechanism in cementitious systems. Glass powder (GP), as a supplementary cementitious material, has demonstrated significant potential in mitigating ASR expansion. This study decouples the ASR inhibition pathways of glass powder (GP) through reactivity and microstructure dynamics. Firstly, amorphous SiO_2 dissolution preferentially consumes hydroxyl ions and calcium, thermodynamically stabilizing pore solution chemistry (Ca/Si >0.4) to limit ASR gel nucleation. Pore refinement caused by the pozzolanic reaction of glass powder reduced porosity and connectivity of cement mortar, kinetically hindering ionic penetration. Concurrently, high-surface-area C-S-H (76.87 m^2/g) adsorbed Na^+, lowering ionic activity and osmotic pressure. Nanoscale analyses revealed that glass powder optimized hydration product polymerization, enhancing gel stability. These multiscale mechanisms of chemical passivation, pore confinement, and gels adsorption collectively disrupted ASR propagation, advancing the design of reactive-additive systems for durable cementitious matrices.

Keywords: Alkali-silica reaction; Glass powder; Particle size; C-S-H gel

Graphical Abstract



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Mechanism on Autogenous Shrinkage of Supersulfated Cement: Insights from Hydration and Microstructure

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Keywords: Supersulfated cement, Mechanism, Autogenous shrinkage, Crystallization pressure, Ettringite

Supersulfated cement (SSC) is gaining increasing attention as a sustainable alternative to ordinary Portland cement (OPC) due to its significantly reduced carbon footprint and improved durability in aggressive environments. Composed primarily of ground granulated blast furnace slag (GGBS) activated by sulfated and alkaline components, SSC can reduce CO_2 emissions by up to 80% compared to OPC. Despite these advantages, its volumetric stability—particularly the behavior of autogenous shrinkage—remains poorly understood, limiting its widespread application in structural concrete. Unlike the well-documented autogenous shrinkage behavior of OPC, which typically involves initial shrinkage, slight expansion, and subsequent shrinkage, SSC exhibits a distinct profile: early-age shrinkage within the first 24 hours, followed by sustained expansion. Understanding this unconventional behavior is essential for improving the dimensional stability and structural reliability of SSC-based systems.

This study systematically investigates the autogenous shrinkage behavior of SSC pastes with varying cement content. A comprehensive experimental program was designed, incorporating hydration kinetics and microstructural characterization. Isothermal calorimetry was employed to monitor early hydration. Mercury intrusion porosimetry (MIP) and Brunauer–Emmett–Teller (BET) techniques were used to analyze pore structure development. Scanning electron microscopy (SEM) provided morphological insights into hydration products, while X-ray diffraction (XRD) confirmed phase composition. Pore solution was extracted at selected ages for ion concentration analysis, which served as input for thermodynamic calculations of ettringite supersaturation and crystallization pressure.
Results show that SSC pastes begin to expand after 1 day of hydration, with the degree of expansion increasing with cement content. In the high-cement-content mix (HE), expansion reached approximately 4500 με at 7 days. This behavior is closely linked to the microstructural features of the matrix. At 7 days, MIP and BET analysis revealed that the volume fraction of gel pores (1–10 nm) in the HE mix exceeded 10%. SEM images further showed a dense, interconnected network of ettringite crystals occupying these fine pores.
Pore solution analysis indicated that ettringite was in a supersaturated state across all samples. Thermodynamic calculations revealed that the expansion region—defined as the pore size range where ettringite crystallization generates pressure—was primarily within the gel pore range (<10 nm). The data suggest that higher cement content leads to finer pore structures and a greater volume fraction of expansion-capable pores.
Although higher cement content slightly reduces the degree of supersaturation and thus the crystallization pressure, the associated increase in expansion region volume fraction results in a higher macroscopic hydrostatic tensile stress. In the HE mix, this pressure was calculated to reach up to 7.61 MPa, accounting for its greater expansion magnitude. These findings confirm that the crystallization pressure of ettringite, constrained within nanoscale pores, plays a dominant role in driving the macroscopic expansion observed during the autogenous shrinkage phase of SSC.
In conclusion, this study provides new insights into the expansion behavior associated with autogenous shrinkage in SSC. It establishes a direct mechanistic link between pore-scale crystallization pressure and macro-scale deformation, and demonstrates how cement content influences both hydration kinetics and

pore structure refinement. These findings deepen the understanding of SSC's volumetric stability and offer practical guidance for optimizing its use in sustainable cementitious systems.

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Metal-Functionalized Biochar: A Dual Approach to Carbon Capture and Mortar Block Reinforcement

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Keywords: Solid waste; Carbon capture; Functional biochar; Green construction; Waste management.

Abstract

Increasing carbon dioxide (CO_2) emissions from cement production, along with solid waste generated from various biomass sources, pose significant challenges to achieving carbon neutrality and require greener and technological innovation. Biochar, a carbon-rich material fabricated by thermally decomposing organic waste, offers sustainable and eco-friendly approaches to reducing CO_2 emissions in concrete production. In the pursuit of carbon neutrality within the construction industry, the current incorporation of small amounts of inert pristine biochar into construction materials is inadequate. This work introduces an innovative approach to address this limitation by transforming a portion of the inert carbon into carbonates, which possess crystal strength and can enhance the properties of construction materials. This transformation is achieved by converting spent coffee grounds (SCG) into potassium (K) and magnesium (Mg) metal-functionalized biochar, referred to as KB and MgB, through a straightforward and efficient process.

Quantitative X-ray Diffraction (Q-XRD) analysis revealed the formation of functionalized products 55.4 wt.% K_2CO_3 in KB and 15.3% $MgCO_3$ in MgB. The formation of K_2CO_3 is primarily due to the release of CO_2 and inert carbon from SCG at elevated temperatures, while the formation of $MgCO_3$ is attributed to the inert carbon from SCG, as confirmed by Q-XRD analysis.

The metal-functionalized biochar produced through this chemical process was subsequently used to prepare mortar blocks, to enhance their mechanical properties. Incorporation of the metal-functionalized biochar at varying levels of 3, 6, 8, and 10 wt.% as partial replacements for cement in the production of mortar blocks is experimented. The findings revealed distinct differences between the two types of biochar. Incorporating KB resulted in a reduction in compressive strength and an increase in water absorption of the mortar blocks. However, the addition of MgB biochar at levels below 8% led to an enhancement in compressive strength and improved water resistance properties. Exceeding this 8% threshold resulted in a decrease in both strength and water resistance. During the functionalization process, a large amount of K_2CO_3 is produced. However, this compound dissolves during the preparation of mortar blocks and does not contribute to strength development. In contrast, $MgCO_3$ remains stable, providing crystal strength and further enhancing the mechanical properties.

In addition to these findings, the workability of the mortar paste was also assessed. The KB mortar paste exhibited reduced workability compared to the control sample, whereas the MgB sample demonstrated better workability than the KB sample. Furthermore, the impact of KB and MgB on the heat of hydration was evaluated. MgB biochar, when used up to 6%, increased the heat of hydration, while the use of KB biochar resulted in a reduction in the heat of hydration compared to the control sample. It was observed that MgB biochar up to 6% decreased porosity by reducing harmful air pores when compared to the control samples. Additionally, the incorporation of MgB up to 6% biochar improved the hardness and elastic modulus.

This research highlights the potential of MgB biochar 6 wt.% as a superior alternative by replacing cement for strengthening mechanical properties, thereby supporting efforts toward achieving carbon neutrality. By repurposing waste materials such as SCG and reducing carbon emissions, this work aims to mitigate the environmental impact of construction practices significantly. This innovative approach not only enhances the mechanical properties of construction materials but also contributes to sustainable development by promoting the use of renewable resources and reducing reliance on traditional cement, which is a major source of carbon emissions. These efforts are paving the way for more environmentally friendly and sustainable construction practices in the future.

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Microstructural Characterization of Low-Clinker Cements: Mechanisms Underpinning Strength and Durability

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Keywords: Low-clinker cement, calcined clay, natural pozzolana, microstructure, strength.

One viable pathway in reducing CO_2 emissions caused by clinker production is the use of low-clinker cements, where supplementary cementitious materials (SCMs) partially replace clinker. In this study, we investigate blended cements with 35% and 45% clinker contents, combined with calcined clay, natural pozzolana, limestone, and calcium sulfate at various proportions. To improve early-age properties, some mixes also include 1.5% sodium sulfate.

The compressive strength of 35% and 45% cement mixed with 45% SCM exceed 30 MPa at 28 days and continue to gain strength thereafter, which is sufficient strength for the market. However, the mechanism behind strength and durability performance of low clinker cements needs to be further investigated to shed light on the hydration products, porosity network, and the evolution of the water populations of the low-clinker systems.

We employ complementary microstructural characterization techniques, including scanning electron microscopy (SEM-EDS), quantitative X-ray diffraction (XRD), mercury intrusion porosimetry (MIP), thermogravimetric analysis (TGA), and dynamic vapor sorption (DVS). The microstructure analysis confirms and support the mechanical and chemical performance of these binders. The results also provide the necessary data for predictive modelling.

On the macroscopic scale, compressive strength of the systems has been measured at 1, 2, 7, 28 and 90 days on standard mortar prisms at water to binder ratio of 0.5.

Calcined clay based systems showed higher compressive strength in comparison to natural pozzolana at all studied ages. This was in accordance with TGA results which indicated higher bound water in calcined clay systems. However, portlandite was depleted in calcined clay cement mixes of both 35% and 45% clinker contents at 7 days according to TG and QXRD results. Due to the lower reactivity of natural pozzolana, portlandite was not depleted, but only showed a reducing trend with age. The total porosity according to MIP measurement was reduced in both calcined clay and natural pozzolana based systems. This reduction is higher with the addition of SCM contents, which is in accordance with the compressive strength results.

In conclusion, our ongoing work aims to clarify how microstructural evolution is linked to mechanical and durability properties, providing a basis for optimizing low-clinker cement formulations.

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Examining the effects of environmentally friendly surface coatings on the corrosion-related mechanical characteristics of copper, aluminum, and carbon steel.

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Keywords: corrosion test; electrochemical test; weight loss test; environmentally friendly coating; mechanical properties.

This study explores the impact of corrosion on the mechanical properties of materials coated with an environmentally friendly substance. The research aims to evaluate the effectiveness of this coating in maintaining the structural integrity of metals used in various applications. The study uses various corrosion tests, including linear sweep voltammetry, open circuit potential measurement, and electrochemical impedance spectroscopy, to evaluate the corrosion resistance of the coated and uncoated samples. Tensile tests are also used to evaluate the mechanical qualities of the materials after exposure to corrosive conditions. The research focuses on carbon steel, copper, and aluminum, which are popular in sectors like construction, automotive, and electronics. The study found that the coating effectively prevents metals from corroding, with the coated aluminum sample showing a larger radius and higher resistance values than the untreated aluminum. The tensile strength of copper was also found to be better than the untreated aluminum. The study provides new insights into the complex interplay between mechanical qualities and corrosion resistance in materials protected by environmentally friendly coatings, which is crucial for industries seeking robust and sustainable solutions for various applications. Further research is recommended to fully understand aluminum behavior in corrosive environments and optimize the coating's performance in various situations.

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Modification of Hemp Shiv Properties Using Novel Functionalized Silica Coatings to Develop Sustainable Thermally Insulated Building Materials

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Keywords: Hydrophobicity, Silica Sol-Gel, Insulation, Bio-Based Material, Dip-Coating

Abstract
The Architecture, Engineering, and Construction (AEC) sector depends heavily on cement and fossil fuels, both of which release high levels of greenhouse gases. These materials contribute significantly to global warming and ozone layer depletion. As a response, the development of sustainable alternatives has become essential. One such material is hemp shiv, a renewable and biodegradable resource capable of capturing CO_2. Hemp shivs can be used as aggregates in hempcrete, a bio-composite material with excellent thermal insulation, fire resistance, and sound absorption. However, untreated hemp shivs are hydrophilic and prone to biodegradation. This study proposes a sol-gelbased surface treatment to modify the properties of hemp shivs. The goal is to improve their durability and functionality without compromising vapor permeability or thermal performance. The treatment transforms the hydrophilic surface into a hydrophobic one by applying a functionalized silica sol gel coating. The process involves synthesizing a silica sol-gel solution using hexadecyltrimethoxysilane (HDTMS), tetraethyl
orthosilicate (TEOS), ethanol, deionize water, and glacial acetic acid. The sol-gel process creates silica nanoparticles functionalized with hydrophobic groups, replacing surface silanols. This modification helps reduce water uptake while maintaining porosity for moisture buffering. Dynamic Light Scattering (DLS) measurements indicated a Polydispersity Index (PDI) of 0.124, confirming a uniform particle distribution and stable sol-gel solution.After dip-coating the hemp shivs and drying, the samples gained 20–30% in mass. This gain is attributed to pore filling and surface layer formation, which prevents excess water absorption. Thermal analysis using Thermogravimetric Analysis (TGA) showed improved thermal stability, with a 63% mass residue retained at 700□ °C for coated shivs. This indicates a slower degradation rate and enhanced fire resistance. Water absorption tests revealed a significant reduction, dropping below 250%. The water contact angle of the coated surface approached 124°, confirming the conversion to a hydrophobic state. Fourier Transform Infrared (FTIR) spectroscopy showed a reduction in water-associated bands between 3200–3500 cm^{-1}, indicating less bound water and successful surface modification with silica.
In conclusion, this study demonstrates that sol-gel-derived silica coatings can significantly improve the performance of hemp shivs for use in sustainable construction. The modified hemp shivs show better resistance to water, improved fire stability, and enhanced thermal insulation, making them viable components in the development of eco-friendly hempcrete for the AEC sector.

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Multiscale Macro-cellulose Fibers reinforced UHPC by synergistic optimization of workability, mechanical performance, and autogenous shrinkage mitigation

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Keywords: Cellulose fibers; UHPC; Shrinkage; Multi-scale reinforcement; Mechanical performance

Ultra high performance concrete (UHPC) is an innovative building material, featuring high strength and remarkable durability against aggressive environments. However, the inherent brittleness and serious autogenous shrinkage of UHPC under low water-to-binder ratios remain critical challenges, often leading to premature cracking and compromised structural integrity. To solve these limitations, fiber reinforcement has been extensively explored to enhance toughness and mitigate autogenous shrinkage.

Recently, cellulose-based fibers have garnered attention because of their wide sources, environmental friendliness and improved compatibility with cementitious matrices. Among diverse cellulosic fibrils types, nano or micro-scale cellulose fibers (e.g., cellulose nanofibrils, CNFs; microcrystalline cellulose, MCC) have been proven efficacy in regulating hydration kinetics and refining pore structures. However, nano or micro-scale cellulose fibers can only function as internal curing agents in UHPC, with little reinforcing effect on UHPC mechanical performance, due to its weak macro-strength compare to the UHPC matrix.

Nowadays, Advances in plant-based fiber processing have unlocked opportunities to engineer macro-scale cellulose fibers with tailored mechanical properties. Bamboo, a rapidly renewable resource with biodegradability and multi-level fiber architecture, presents a promising UHPC additive. Researchers used bamboo to obtain an improved macro-cellulose fiber (MCF) composed of highly dense arrangement of nanocellulose. Physical and chemical improvement methods were applied to remove components such as lignin and hemicellulose. This kind of MCF engineered through a combined chemical-mechanical treatment, which removes components such as lignin and hemicellulose, retaining high cellulose content (>90%). In addition, this MCF achieves a tensile strength of 1.8 GPa, surpassing most synthetic polymeric fibers such as PP and PVA fibers. If this bio-based MCF can be applied to UHPC, it will not only be in line with the initiative of green building materials, but also have a dual advantage of cellulose and macroscopic fibers.

To explore the reinforcement mechanism of macro-cellulose fibers in UHPC, this study combined micro-cellulosic fibrils to elucidate the multi-scale effects of size differences of cellulose fibers on the fresh state properties, autogenous shrinkage, hydration kinetics, mechanical properties, and pore structure of UHPC. Results show that macro-cellulose fibers result in minimal interference with UHPC's workability and lower dynamic yield stress, plastic viscosity due to its lower capacity of water competes with cement and more difficult fiber entanglement, which further promotes denser matrix structure than the micro-cellulosic fibrils. Hydration calorimetry reveals macro-cellulose fibers' tinier retardation effect compared to micro-cellulosic fibrils, enabling an accelerated hydration process. Mechanically, macroscale fibers enhance 28-day compressive and flexural strengths through effective macrocrack bridging and refinement of harmful pores.

The monitoring of autogenous shrinkage and microstructure analysis reveals key information: smaller fibers exacerbate micropore formation despite the superior shrinkage control than macro-cellulose fibers. These findings establish a multi-fiber-sized system, providing a theoretical framework for optimizing cellulose reinforced UHPC system that balances processability, durability, and structural performance.

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Novel interlocking nozzle geometry for enhanced interlayer strengthening in 3D concrete printing

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Keywords: 3D Concrete Printing, Interlayer Bonding, Nozzle Geometry, Mechanical Interlock, Interlayer shear strength

3D Concrete Printing (3DCP) represents a pioneering advancement in the construction industry, leveraging additive manufacturing techniques to fabricate complex concrete structures with precision and efficiency. However, the mechanical integrity of 3D-printed concrete is often compromised at the interfacial regions between layers, which exhibit weaker mechanical properties than traditionally cast materials. This inherent weakness at the interface leads to a significant reduction in overall structural performance.

This study investigates the enhancement of interlayer bonding strength through the development of a novel interlocking nozzle geometry in the 3D concrete printing process. The proposed nozzle design aims to create mechanical interlocks at the interface of successive vertical and horizontal layers, thereby increasing the contact surface area and enhancing shear resistance. By optimizing the shape of the nozzle, the printed layers exhibit a unique interlocking pattern that counteracts delamination and improves load transfer across layers.

Experimental trials were conducted using a custom-designed nozzle, tailored to produce the interlocking geometry. Concrete specimens were printed and subjected to interlayer shear strength, flexural performance, and compressive strength assessments. The mechanical properties of these interlocked samples were compared against control samples printed using conventional flat nozzles. The results demonstrated a marked improvement in interlayer shear strength, with the interlocking geometry providing enhanced cohesion between layers.

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Optimizing Graphene Oxide Dispersion in Cement Composites: Effects on Microstructure and Mechanical properties

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Keywords: Graphene Oxide, Cementitious materials, Superplasticizer Dispersion techniques, Microstructure development

The incorporation of graphene oxide (GO) in cementitious materials has received significant attention due to its ability to improve mechanical performance and durability. GO's unique two-dimensional structure, high surface area, and functionalized nature enable it to interact with cement hydration products, refine microstructure, and increase strength. However, the efficiency of GO reinforcement largely depends on its dispersion state, as improper dispersion leads to agglomeration, which may significantly decrease its interaction with the cement matrix. Despite ongoing research, the most effective dispersion techniques and their direct effect on microstructural development and mechanical properties remain largely unexplored. This study aims to evaluate the reinforcing mechanism of GO in cementitious substances by comparing the effects of different dispersion techniques on GO stability, microstructure, and hydration characteristics. To achieve this, several dispersion techniques were examined, with a focus on two essential parameters: (i) the time of superplasticizer (PS) introduction during ultrasonication and (ii) the duration of ultrasonication conducted to the GO solution. In the primary technique, PSs were introduced at different times during ultrasonication to investigate their influence on GO stability and dispersion. In the second technique, the ultrasonication duration is varied while keeping an optimal PS addition time to evaluate the effect on exfoliation and suspension stability. The dispersion degree of GO suspensions was examined using UV-visible spectroscopy and particle size distribution analysis, providing insights into GO exfoliation and balance. Furthermore, the interaction between GO and the cementitious matrix was studied using X-ray diffraction (XRD), scanning electron microscopy (SEM), and nuclear magnetic resonance (NMR). The XRD gave information on the phase shifts that occur in cement during hydration, while the SEM produced images of the GO dispersion throughout the cement matrix, and the NMR provided insights into the effect of GO on silicate polymerization and hydration kinetics.

The experiments confirmed that the timing of PS introduction has a significant impact on how GO disperses, with late introduction improving exfoliation and stability. UV-visible spectroscopy revealed that GO suspensions with PS introduced later in the technique had higher absorbance values, indicating better dispersion and less agglomeration. Particle size analysis indicated that later PS introduction resulted in finer, more evenly dispersed particles, indicating improved suspension stability. The second dispersion technique demonstrated that ultrasonication time is important for breaking down GO clusters and ensuring uniform dispersion. However, beyond the optimal ultrasonication time, no significant improvement was observed. SEM imaging provided clear microstructural evidence that well-dispersed GO is better incorporated into the cement matrix, resulting in a denser and more homogeneous structure. Furthermore, the NMR study revealed increased polymerization of the silicate network, demonstrating that well-dispersed GO impacted the hydration behavior, resulting in improved mechanical performance of the composite material.

These findings highlight the importance of using suitable techniques for dispersing GO into cementitious materials to achieve maximum reinforcing potential. The study demonstrates that the timing of PS introduction during ultrasonication and the duration of ultrasonication are both critical for achieving a well-

dispersed GO suspension, as they affect the development of microstructures and mechanical performance. The current study provides insights into the effective use of GO in nano-engineered cement-based materials with increased mechanical strength and durability by demonstrating the clear connection between dispersion quality and the development of the water-cement microstructure.

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Penetration test of sheet-like indenter for early age yield stress assessment of 3D printed concrete

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Keywords: 3D-printed concrete; yield stress; penetration test; sheet-like indenter

In the field of early performance characterization of 3D printed concrete, penetration testing, as a newly developed testing method, has been widely applied. In existing research on penetration testing, the influence of the side of the indenter is often simplified, or the indenter whose side does not contact with the material is used. Whether the interaction between the side of the indenter and the material can provide effective information for the characterization of the early rheological properties of concrete is a problem worth studying. In this work, we designed various sheet-like indenter structures to amplify the interaction area between the indenter side and the cement-based materials upon deposition. First, we show the mechanical curve of sheet-like indenters with different surface roughness during the penetration test and analyze the main factors affecting the penetration resistance at different stages of penetration. The experimental results show that the force-displacement curve in the penetration test shows two different regimes for the intender without low surface roughness. At the beginning of penetration, the slope of the curve is relatively high. After reaching a certain depth, it enters a regime of approximately linear steady with a relatively low level. Then, we deduce the correlation between the yield stress and the obtained force-displacement curves. The influence factors on the curve are summarized as the combined action of normal compression, shear motion, and slipping. Moreover, we verified that by the design of a rough surface of the indenter, the shear motion can play a major role in the steady rise stage. Finally, a formula for assessing the yield stress of the material based on the shape of the force-displacement curve is established. The proposed penetration test approach for sheet-like indenters is finally verified to be a feasible and reliable method for obtaining the yield stress development of 3D-printed cement-based materials.

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Pressure-Induced Fabrication of Transparent Cement: A Biomimetic Strategy for Inorganic Material Optimization

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Keywords: Transparent cement; Amorphous calcium silicate hydrate;High-pressure processing; Biomimetic fabrication

Abstract: Traditional Portland cement has long been constrained in applications for smart buildings and functional construction materials due to inherent limitations in light transmission and mechanical performance caused by pores, grain boundaries, and defects within its polycrystalline structure. In nature, organisms such as mollusks employ amorphous precursor-controlled assembly and densification strategies—exemplified by the formation of calcium carbonate-based nacre—to create high-performance inorganic materials, offering novel insights for advanced fabrication techniques. Inspired by these biomineralization principles, this study proposes a biomimetic strategy combining high-pressure processing with trace organic polymer additives to transform cement-based materials from conventional polycrystalline architectures into amorphous continuous phases, resulting in the successful development of transparent cement. Experimental results demonstrate that this high-pressure densification process effectively eliminates internal pores and grain boundaries, achieving 85% optical transmittance while simultaneously enhancing mechanical properties, thereby establishing a new paradigm for functional inorganic construction materials.

By introducing the "amorphization-densification" mechanism of biomineralization into cement systems, extreme pressure drives structural reorganization of the cement matrix. On one hand, high pressure induces coalescence of C-S-H gel particles, closing pores and reducing grain boundary density to form an amorphous calcium silicate hydrate network characterized by long-range disorder and short-range order. On the other hand, first-principles calculations reveal that organic additives exhibit strong chemisorption with surface Ca^{2+} ions on C-S-H, preferentially occupying crystal nucleation sites to suppress Ostwald ripening. Concurrently, flexible polymer chains mitigate interfacial stress concentration through dynamic deformation, effectively preventing microcrack initiation during densification. The optimized transparent cement achieves an average visible light transmittance of 85%, comparable to commercial soda-lime glass, while nanoindentation tests demonstrate remarkable mechanical properties with hardness and Young's modulus reaching 1.8 GPa and 40.7 GPa, respectively—representing a 50% improvement over conventional cement and surpassing certain engineering ceramics. XRD-RDF analyses confirm the preservation of short-range ordering in $[SiO_4]^-$ tetrahedra and Ca^2 coordination within the amorphous C-S-H matrix, whereas long-range disorder eliminates light scattering from grain boundaries. Density functional theory calculations further reveal that high pressure enhances hybridization between O-2p and Ca-3d orbitals, widening the bandgap to promote structural amorphization. The synergistic role of organic additives reduces surface energy in nano-C-S-H particles, inhibiting Ostwald ripening and ensuring nanostructural stability.

The breakthrough properties of transparent cement unlock multidimensional applications in green building technologies. As a proof-of-concept, fluorescent molecules encapsulated within the cement matrix enable optical functionalization for architectural applications. Its high transparency and mechanical strength make it ideal for intelligent building envelopes: integration with thermochromic coatings could enable dynamic

daylight regulation to optimize energy efficiency, while coupling with perovskite photovoltaic films may yield building-integrated power systems that simultaneously serve structural and energy-generating functions. Crucially, the proposed "amorphization-densification" strategy exhibits universal applicability, allowing synergistic optimization of strength, functionality, and processability in inorganic materials through tailored pressure gradients and additive molecular engineering. Future research will prioritize the development of low-pressure fabrication techniques, long-term stability assessment of organic-inorganic interfaces, and cost-effective scaling strategies to transition this innovative material from laboratory prototypes to practical engineering applications, thereby advancing the green building revolution in alignment with global carbon neutrality goals.

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Properties of low-carbon UHPC using alkali-activated binder

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Keywords: Ultra-high performance concrete; UHPC; Alkali-activated material; Wollastonite.

Ultra-high performance concrete (UHPC) is a fibre-reinforced concrete known for its exceptional mechanical properties, toughness, and durability. It is typically made of ordinary Portland cement (OPC) and supplementary cementitious materials (SCMs), combined with fine aggregates, fibres, superplasticizers, and minimal water. Despite its superior performance, UHPC typically contains two to three times more OPC than conventional concrete, leading to a significant environmental impact from OPC production that compromises the material's sustainability. This has prompted the exploration of OPC-less UHPC as a more sustainable alternative. In recent years, alkali-activated binders have emerged as a prospective alternative to OPC due to their significant reduction in carbon footprint by recycling industrial by-products or wastes as source materials and/or activators. Motivated by this advantage, this study aims to develop a low-carbon UHPC, known as alkali-activated UHPC (A-UHPC), by complete replacement of OPC with alkali-activated materials. The influence of incorporating wollastonite on the fresh and hardened properties of the developed A-UHPC has been investigated. Wollastonite is a natural fibrous mineral produced through an environmentally friendly process, offering a unique fibre structure that can enhance the reinforcing properties of concrete. The results showed that the compressive strength of all mixtures exceeded 120 MPa, with the maximum compressive strength reaching 147.8 MPa with 10% wollastonite incorporation. The compressive strength of the mix without wollastonite was comparable to that of the mix containing 10% wollastonite, whereas the flexural strength of the mix without wollastonite was 42% lower than that of the mix with wollastonite. This confirms that the incorporation of wollastonite had a significant positive effect on the flexural strength, while the compressive strength remained largely unaffected, highlighting its potential as an effective reinforcing agent in the A-UHPC. In the case of mixes containing wollastonite with varying water-to-binder ratios, reducing the water ratio led to a significant 18% increase in compressive strength, while flexural strength decreased by 15%. To ascertain the material's sustainability of the developed A-UHPC, a conventional UHPC mixture from the authors' previous studies was selected for comparison. This reference mixture was chosen because its mechanical properties were comparable with those of the highest-strength A-UHPC mix produced in this study. Both mixtures were subjected to identical curing conditions and tested for strength using the same equipment, enabling a direct and meaningful comparison of their performance and sustainability. The material sustainability calculations confirmed the developed A-UHPC is a promising low-carbon alternative to typical UHPC offering 30% less carbon emissions and 15% less energy consumption. The corresponding unit embodied energy per compressive strength of A-UHPC and the typical UHPC are 86.2 and 103.5 MJ/kg/MPa, respectively, and their unit carbon emissions per compressive strength are 6.8 and 9.9 kg/kg/MPa, respectively. The main difference in the environmental impact of the two mixtures comes from the production of OPC

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Properties of ultra-high-performance concrete produced using untreated and treated recycled fine aggregates

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Keywords: Ultra-high-performance concrete, recycled fine aggregates, fly ash, volcanic ash

Ultra-High-Performance Concrete (UHPC) holds significant importance in the construction industry due to its excellent mechanical strength and durability. Its superior compressive and tensile strength allows for thinner structural elements, reducing material usage and construction weight. The use of recycled aggregates in concrete production is a sustainable solution to address the growing environmental concerns associated with natural aggregate exhaustion and construction and demolition waste. However, untreated recycled aggregates often exhibit higher water absorption, lower density, and weaker bond strength due to residual mortar and microcracks. Treating recycled aggregates, such as with mineral-based slurries like volcanic ash or fly ash, enhances their surface properties, reduces water absorption, and improves the interfacial transition zone in concrete.

In this study, recycled fine aggregates (<4.75 mm) were treated with the volcanic ash and fly ash slurries to improve their performance in concrete applications. The aggregates were first cleaned to remove debris and dried to ensure proper adhesion of the coating. Slurries of volcanic ash and fly ash were prepared by mixing volcanic ash and fly ash in water. The recycled aggregates were then coated with the slurry in a concrete mixer, ensuring even distribution. The coated aggregates were air-cured for 24–48 hours, followed by water curing for 7–14 days to enhance the bonding strength of the coating. The water absorption, density and specific gravity of untreated and treated recycled aggregates were determined. The water absorption reduced significantly, while specific gravity and density of recycled fine aggregates increased after the treatment with slurries of fly ash and volcanic ash. The fly ash slurry was found to be more effective in improving the properties of recycled fine aggregates.

Untreated and treated recycled aggregates were then utilized to prepare ultra-high-performance concrete (UHPC) mixes. Four UHPC mixes were prepared using natural fine aggregates (UHPC-C), untreated recycled fine aggregates (UHPC-UT), fly ash treated recycled fine aggregates (UHPC-FA), and volcanic ash treated recycled fine aggregates (UHPC-VA). Flow, compressive strength, water absorption and volume of permeable voids tests were determined for all the UHPC mixes. The control mix (UHPC-C) exhibited the highest compressive strength (138.6 MPa) and superior durability parameters, with minimal water absorption (0.95%) and void content (1.15%), confirming its high-performance characteristics. However, UHPC-UT showed a significant reduction in compressive strength (114.5 MPa), coupled with higher water absorption (2.1%) and void content (3.2%), indicating a compromise in both strength and durability. In comparison, UHPC-FA and UHPC-VA demonstrated compressive strengths of 125 MPa and 122.9 MPa, respectively, with improved durability characteristics relative to UHPC-UT. Both mixes exhibited comparable water absorption (approximately 1.9%) and void content (around 2.1%), highlighting the potential of fly ash and volcanic ash as sustainable alternatives to traditional binders in UHPC.

These findings highlight the importance of material selection in optimizing the balance between mechanical properties and durability in UHPC mixes. The study concludes that while the control mix offers incomparable performance, UHPC-FA and UHPC-VA provide promising sustainable alternatives with minimal compromise in properties.

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Relationships between yield point and slump test spreading for high yield point materials

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Keywords: yield stress, Slump test, high yield stress material

Abstract :

The cone or mini-cone slump test is the most common method to evaluate the flow properties of liquid materials. Although slump provides a qualitative measure of workability, the relationship between slump and more quantitative rheological parameters is not fully understood.
In this study, we propose a new dimensionless method and model relating slump to yield stress, for not only fluid materials, but for materials with a high yield stress. This method consists of forcing the material to sag in a cylinder using weights fig. 1., this method developed and generalized according to the dimensions and geometry used. The chosen material is cement paste. To increase or decrease the workability of the latter, we varied the W/C ratio. The yield stress measurements of the cement paste used are carried out using rheometer with stress controled, equipped with a bladed mobile, subsequently these measurements are compared to the slump measurements in a cylindrical geometry. The cylindrical slump model is in excellent agreement with the experimental data of the yield stress obtained using the rheometer. Most of the other slump models available in the literature, concern only fluid materials, Several researchers have proposed an empirical equation to relate the yield point to the volume of the mold (mini-cone) and to the final diameter at the stop of the flow of the slumped paste called final spreading. The model created is based on the postulate that the phenomena are controlled only by the self-weight of the material. According to our knowledge, a large divergence has been recorded between the empirical equations and the rheometric measurements in the case of materials with high yield point. The cylindrical slump model is in excellent agreement with the experimental data of the yield stress obtained using the rheometer.
Most of the other slump models available in the literature, concern only fluid materials.
According to our knowledge, a large divergence has been recorded between the empirical equations and the rheometric measurements in the case of materials with high yield stress.

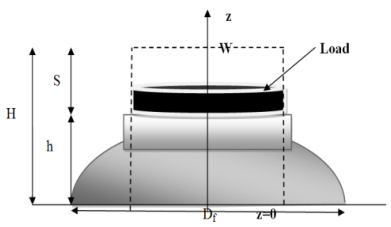

Fig. 1: Cylindrical slump

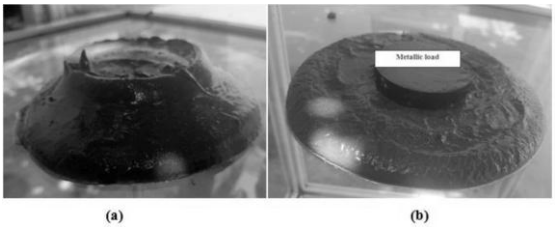

Fig2: Spreading (a) without load and (b) under load

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Research on Temperature Control and Crack Prevention Simulation Method for Mass Concrete with Complex Components Based on Deep Learning

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Keywords: concrete, deep learning, prediction model, thermal cracking.

Temperature control and crack prevention of mass concrete are significant to the safety and durability of structures such as dams and long-span bridges. Adiabatic temperature rise and mechanical properties are the key issue in thermal and crack risk analysis of mass concrete. Due to the substantial diversity of admixtures influencing the hydration process in modern concrete, it is challenging to develop a comprehensive analytical model to predict adiabatic temperature rise, compressive strength, tensile strength, and modulus of elasticity (MOE) based on theoretical frameworks. The deep learning (DL) model gives a feasible approach as data-driven methods for accurate prediction of various material properties these years. However, predicting time-dependent thermal and mechanical properties of modern concrete with complex mix constituents by DL algorithms is still confined so far.

DL model based on artificial neuron network (ANN) and recurrent neuron network (RNN) were employed in this study to predict adiabatic temperature rise considering 15 variables as input parameters. The determination coefficient (R^2) of the prediction results given from ANN and RNN were 0.7616 and 0.8542, respectively. Segmentation technique and bidirectional deep (BD) neuron network algorithm were implemented to improve the performance of RNN. It was demonstrated that BD-RNN provided better results with promising statistical parameters (R^2=0.9245) and curve fitting of adiabatic temperature rise profiles. Through optimization and k-fold cross-validation, an evolutionary DL model was developed for reliable prediction of adiabatic temperature rise of concrete with complex admixtures. ANN and long short-term memory (LSTM) based DL models were established to predict concrete compressive strength, tensile strength, and MOE at different ages, considering the mix design, curing condition, curing time and tension testing method as input variables. LSTM outperformed ANN in terms of the statistical indicators for accuracy evaluation with high training and testing time costs. Bidirectional modification and multi-head attention mechanism were implemented to further improve the prediction accuracy of LSTM. It is shown that the multi-head attention bidirectional LSTM had more precise predicting results (R^2=0.9355 for compressive strength, R^2=0.8930 for tensile strength, R^2=0.9584 for MOE) and fitting of the mechanical property-age curves.

The theoretical foundation and simulation principles of the temperature field in mass concrete were derived in this study. Based on these theories, a model is established for the open section of the Guangzhou New Baiyun Airport Second Expressway Tunnel project. The adiabatic temperature rise curves of the concrete in this project are calculated using the BD-RNN model developed in this study, as well as classical fractional and exponential mathematical models. These curves are then used as input parameters for the established temperature field simulation model. By comparing the simulated results with the measured temperatures from embedded concrete sensors, the optimal input parameters are selected. Finally, the evolution of the temperature field in the mass concrete of the open section is analyzed. Furthermore, the theoretical framework of the stress field in mass concrete is derived. Based on this theory, a model is established for the open section of the tunnel project. The MA-BiLSTM model developed in this study is employed to predict the evolution curve of the concrete's elastic modulus, which is used as one of the input parameters for simulating the stress field of the concrete structure. The evolution patterns of the stress field in the base slab and side walls are analyzed. Furthermore, in combination with the time-dependent tensile strength of concrete predicted by the MA-BiLSTM model, the cracking risk of mass concrete in the actual project is assessed.

The results showed that DL models developed in this study could precisely predict the time dependent thermal and mechanical properties of concrete based on mix designs and curing conditions. These properties could be used as key

input parameters for the temperature field and stress field model developed in this study. The temperature field simulation model and stress field simulation model could accurately evaluate the risk of thermal cracking for concrete.

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Self-Sensing Mineral-Impregnated Carbon Fiber Reinforcements for the Detection of Moisture Ingress

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Keywords: Carbon fiber; Moisture detection; Intelligent infrastructure; Self-sensing composites; Mineral impregnation;

Growing cargo traffic and increasing mobility demands on the road infrastructure are creating significant economic and ecological challenges. A long and sustainable service life of concrete composites highly depends on a continuous monitoring of conditions, which forms the base for timely maintenance, rehabilitation, and upgrading strategies. Replacing conventional steel or fiber-reinforced polymer (FRP) reinforcements, mineral-impregnated carbon fibers (MCFs) have emerged as a novel reinforcement type for construction. This approach delivers primary benefits in implementation, cost-effectiveness and temperature resistance in applications [1,2].

The objective of this paper is to expand the self-sensory capabilities of MCF elements by activating intrinsic electrical properties of CFs to detect the ingress of moisture. To proof this concept, water absorption and desorption behavior of MCF composites were systematically investigated under various conditions. In particular, the MCF microstructures were tailored using different water-to-binder ratios allowing controlled porosity features. The MCF composites were fabricated via automated pultrusion using a cement-based impregnation suspension, achieving uniform uniaxial fiber alignment and appropriate electrical resistivity (11 Ω·μm). All produced MCF reinforcements demonstrated a clear sensitivity to detect moisture ingress through resistivity-based self-sensing mechanisms. With varying porosities, the smart reinforcements exhibited distinct trends when exposed to different wetting conditions, indicating their potential application in functional monitoring of road infrastructure. Mercury intrusion porosity measurements corroborate the distinct differences in pore structure of the MCFs. From these outcomes, a route towards appropriate integration of mineral matrix composite-based sensors into civil infrastructure can be developed, including traffic applications such as autonomous vehicles and Industry 4.0.

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Sequestration capacity of selected waste ashes and influence of carbonation on leaching behaviour

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Keywords: accelerated carbonation, CO_2 sequestration capacity, leaching, heavy metals, waste ash

Introduction

This study investigates the CO_2 sequestration capacity of six fully carbonated ash types, including three from wood biomass and three from co-combustion processes. Since carbonation can significantly influence the leaching behaviour of these materials, special focus is placed on the stabilization of heavy metals in carbonated ash, offering a promising strategy for enhanced waste management.

Experimental

All ash samples were homogenized by quartering. Before chemical analysis, samples were dried to a constant weight in a laboratory oven at 105 °C and then ground to pass through a 125 μm sieve. The loss on ignition (LOI) was determined by heating the samples at 950 °C according to the EN 196-2:2013 standard. The chemical composition of the ash was analysed using an X-Ray Fluorescence Spectrometer. Fourier Transform Infrared Spectroscopy (FTIR) was performed in attenuated total reflectance (ATR) mode before and after CO_2 exposure. A calibration curve was generated using calcite and quartz standards with known concentrations. For mineralogical analysis, each ash sample was further ground and sieved to below 63 μm. X-ray diffraction (XRD) analysis was conducted before and after CO_2 exposure using an X-Ray Diffractometer with a Cu X-ray source, scanned in 0.013° increments from 4° to 70° under clean room conditions.

The CO_2 sequestration capacity of each ash sample was evaluated under controlled carbonation conditions: 80 ± 1 % of relative humidity (RH), a temperature of 40 ± 0.1 °C, and a CO_2 concentration of 4±0.1 vol%. Before accelerated carbonation process, the ashes were sieved to a particle size below 125 μm and then placed in a closed carbonation chamber. The samples were weighed at different time intervals until a constant mass was achieved. Fully carbonated samples were dried at 105 °C for 24 hours for further analyses, including calcimetry, thermogravimetric analysis (TGA), XRD and FTIR. The CO_2 content (wt.%) in the ash was determined using TGA and calcimetry. Using calcimetry, which quantifies carbonate content based on its reaction with acid, CO_2 release was measured with a pressure calcimeter according to ASTM D 4373. The calcimeter was calibrated prior to measurements by reacting HCl with standard $CaCO_3$. TGA was performed in an inert atmosphere on dry carbonated samples using a thermal analyser, from 25 to 1000 °C at a heating rate of 10 K min^{-1}.

For leaching tests, the EN 12457-2:2002 leaching procedure was selected. Leaching was performed by suspending 2.0 g of ash in 20 mL of distilled water (L:S=10). After 24 h of agitation, the suspension was

filtered, and pH and conductivity were measured. Chloride (Cl^-) and sulphate (SO_2^{4-}) concentrations were measured in the filtrate by ion chromatography (IC); while the concentrations of Ca, K, Cd, Cr, Cu, Ni, Pb and Zn were analysed using inductively coupled plasma-optical emission spectroscopy (ICP-OES).

Results

The CO_2 uptake was determined using a pressure calcimeter based on the CO_2 content before and after accelerated carbonation. The maximum CO_2 uptake was 17.1% for wood fly ash and 19.2% for co-combustion ash from a paper mill using a fuel mixture of paper fiber sludge, wood waste and bark. Waste ashes showed significant potential for carbon sequestration, with CO_2 sequestration capacities of up to 432 g per kg of wood ash and up to 380 g per kg of co-combustion ash. To increase the efficiency of sequestration, it is crucial to maintain an optimal pH value. The initial pH of the untreated ash was remarkably high (up to pH=13), while the pH decreased after carbonation. At the maximum sequestration capacity achieved for wood ash, the corresponding pH decreased from 13 to 10. The carbonation reactions with the formation of $CaCO_3$ cause the pH to decrease to a less basic value, reducing the solubility of metallic hydroxides and increasing the stability of heavy metals such as Zn and Cu. The concentrations of Cu decreased by up to 85% in the analysed samples, indicating that harmful metals could be trapped in the carbonated ash. The leaching of Zn is strongly dependent on the K concentration and the leaching of SO_4^{2-}, with the Zn concentration being highest in wood fly ash with the highest K concentration and the highest concentration of soluble SO_4^{2-}.

Conclusions

Carbonation affects materials through pH changes, metal carbonate precipitation, and mineral interactions, all shaped by carbonation conditions and the original mineralogy. All these factors may affect to the leaching of toxic elements. There is National or Community legislation that requires an assessment of toxic species and restricts the use of products if values are exceeded. Therefore, leaching tests are essential for assessing the environmental impact and sustainability of building materials.

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Structural Reliability Assessment of Periwinkle Shell-Natural Aggregate Reinforced Concrete Beam Subjected to Bending Forces

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Abstract
Recently, studies related to the assessment of fatigue and reliability of structures have increased. This paper presents the reliability assessment of a reinforced concrete beam subjected to Bending force. Locally available natural aggregate (NA) was partially replaced with Periwinkle shell and used in concrete production. A typical beam with cross section of 4000 × 400 × 225 mm beam was adopted and probabilistically assessed. First Order Reliability Method (FORM) was employed to estimate the implied probabilities of failures. The results of the sensitivity analysis showed that the reinforced concrete beam produced incorporating Periwinkle shell is structurally safe at length and depth of 3100 and 600 mm with Probability of Failures of 1.26×10^{-3} and 5.77×10^{-4} respectively.

Keywords: Beam, Bending, Concrete, Natural aggregate, Periwinkle, Reliability.

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Theoretical model of effective elastic moduli of two-dimensional two-phase composites considering inclusion shape, arrangement, and volume fraction

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Keywords: n-point correlation function; Lattice model; Effective elastic moduli; Two-phase composite; Three-point approximation

Abstract

One area of study in civil engineering materials is the mechanical properties of cementitious composites. The mechanical properties of cementitious composites are significantly influenced by their compositional parameters. Because of the numerous internal components and intricate structural features, it is challenging to measure the relationship between internal component characteristics and cementitious composites' mechanical properties using current experimental research methods. One of the main challenges in the current research on cementitious composites is quantifying the intricate relationship between the mechanical properties and the internal component characteristics. Cementitious composites can be thought of as two-phase composites with a particle phase and a matrix phase on the mesoscopic scale. The internal structure of cementitious composites is greatly influenced by the properties of these particles, which have certain laws of size and form. This, in turn, has a significant impact on the mechanical properties of cementitious composites. Investigating how particle characteristics affect the mechanical properties of cementitious composites is crucial.

First, the geometrical construction of particles, the overlap criterion of particles, and the basic concepts of the discrete element method are combined to produce a new dynamic packing algorithm based on function expression that can be applied to many particle shapes. The mobility state and interaction link between non-spherical particles are taken into account by the new method. This algorithm successfully establishes the stable dynamic packing system of non-spherical particles. Second, to obtain the statistical quantitative results of the particle packing structures, a new quantitative characterization technique that is applicable to non-spherical particles has been successfully developed. This technique is based on the dynamic packing system of particles, the overlap criterion of particles of different shapes, the basic principle of the n-point correlation function, and the adaptive triangulation method. Furthermore, by combining the overlap criterion of particles of diverse shapes with the fundamental idea of the lattice model, a new numerical simulation method suitable to non-spherical particles has been successfully created for predicting the mechanical properties of cementitious composites. The theoretical prediction model that reveals the relationship between the characteristics of the internal composition contained and the effective mechanical properties of cementitious composites has finally been developed. It is based on the fundamentals of solid mechanics and composite mechanics and is supported by statistical quantitative results obtained by recently developed quantitative characterization techniques. Additionally, the reliability of the recently proposed theoretical prediction model is confirmed by the effective mechanical property findings computed using the recently established numerical simulation method based on the mesostructure model of cementitious composites. The coupling effects of aggregate particle size, shape, spatial arrangement, and volume percent

on the effective bulk modulus and shear moduli of cementitious composites are accurately measured using the newly created modified three-point approximation.

According to the results of the theoretical and numerical studies, the cementitious composites' effective bulk and shear moduli rise as the volume percent of aggregate particles increases, and the increases become more noticeable at higher volume fractions. The effective transverse bulk and shear moduli of the aggregate particles' four distinct planar layouts can be arranged as follows at high particle volume fractions: Regular triangle arrangement<random arrangement<regular square arrangement<regular hexagon configuration. The effective transverse bulk and shear moduli of cementitious composites decrease when aggregate particle circularity decreases at high particle volume fractions. The effective transverse bulk modulus of cementitious composites with aggregate particles of various shapes can be graded as follows: convex ellipse≈convex oval<concave ellipse≈concave oval when the particles' circularity is low. When the circularity of the particles is elevated, the effective transverse bulk modulus of cementitious composites containing aggregate particles of various shapes can be ranked as convex ellipse>convex oval>regular polygon. The influence of particle morphology on the effective transverse shear moduli of cementitious composites is minimal.

This work develops a quantitative model of the "internal composition-mechanical properties" of cementitious composites to predict the complex link between internal compositional traits and mechanical qualities. The results of this study provide a valuable framework for the design of cementitious composites and the selection of engineering materials.

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Sustainable Reproduction of Ornamental Glass for Historical Building Retrofitting: A Dual-Material Approach Using Refractory and Alkali-activated Concrete

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Keywords: Refractory concrete, alkali-activated binders, ornamental glass, heritage conservation, sustainable retrofitting.

Introduction

Historical buildings from the 18th to early 20th centuries, such as churches, palaces, theaters, and museums, often feature ornamental glasswork integral to their architectural identity. Notable examples include Baroque churches in Central Europe, Victorian theaters in the UK, Art Deco civic structures in the U.S., and colonial-era palaces in South Asia. However, retrofitting these delicate glass windows presents significant challenges. The industrialized glass industry prioritizes large-scale production with embossed steel rolls, making it costly and inefficient to reproduce nowadays small, customized batches of "old ornamental" glass for heritage projects.

To produce small batches of true to original ornamental plate glass, refractory moulds which contain the pattern of the original ornamental glass are used. The moulding process means, that the refractory mould is heated up to the softening point of plate glass. The softened glass assumes the present pattern of the refractory mould.

This research proposes an innovative dual-material approach: classical refractory concrete for high-temperature resilience and alkali-activated binders for sustainable, low-waste molding. By integrating these materials, this study presents an adaptable and economically viable solution that meets the diverse demands of heritage conservation while reducing environmental impact.

Methodology

Two material systems for mold fabrication were assessed, adhering to ASTM (USA), EN (European), and DIN (German) standards to ensure global applicability.

Refractory Concrete:

- Composition: Alumina-silicate aggregates bonded with calcium aluminate cement – used as a ready-mixed compound.
- Performance Focus: Thermal stability (tested up to 800°C per DIN 4102-2 for fire resistance) and mechanical durability.

Alkali-activated Concrete:

- Composition: Alkali-activated metakaolin and slag.
- Performance Focus: Workability and high-performance synthesis compliant with EN 197-1 (cement standards).

Experimental Framework:

1. Material Optimization: Iterative mix ratio adjustments to balance thermal resistance (refractory) and curing efficiency (alkali-activated binders)
2. Performance Evaluation: Workability and eco-friendly synthesis, compliant with EN 197-1 (cement standards).

- Mechanical Properties: Compressive strength (ASTM C39; EN 12390-3) and Flexural strength (ASTM C78; EN 12390-5).
- Thermal Behavior: Cyclic heating tests (DIN 4102-2) to simulate glass-slumping conditions.
- Shrinkage and Durability: Post-curing dimensional analysis (EN 12617-4) and post-firing structural integrity.

Process Refinement:

- Heating curve calibration for glass slumping to ensure design fidelity.
- 3D profilometry to quantify mold-to-glass surface replication accuracy.

Results and Discussion

Material Performance:

- Refractory Concrete: Achieved 55 MPa compressive strength (EN 12390-3) and ⩽ 1% deformation at 800°C (DIN EN 14486-2, DIN 4102-2), proving ideal for high-temperature applications.

- Alkali-activated Concrete: Delivered 50 MPa compressive strength (EN 12390-3) with <1% shrinkage (DIN EN 14486-2, DIN 4102-2).

Operational Efficiency:

Custom molds reduced the material waste by a considerable percentage compared to mass production, aligning with EN 15804 (sustainability criteria). Cost savings of 35% for small-batch projects, critical for underfunded heritage sites, such as colonial-era palaces in India or Art Deco theaters in the U.S.

Global Implications:

- Developed Nations: Enables high-precision replication of intricate designs, ensuring compliance with stringent heritage guidelines (e.g., EU's Venice Charter, DIN 18217 for construction tolerances, and ASTM E2727 for historic preservation).
- Underdeveloped Regions: Alkali-activated concrete's reliance on local byproducts (e.g., fly ash in India, slag in Brazil) reduces dependency on imported materials, making retrofitting more accessible while meeting EN 206 concrete performance standards.
-

Critical Analysis:

While the dual-material approach offers significant advantages, challenges remain:

1. Scalability Concerns:
    - Refractory concrete's rapid curing demands skilled labor, potentially increasing costs.
    - Alkali-activated binders synthesis requires precise pH control, posing difficulties for large-scale adoption.
2. Specialized Training Needs:

- Complex restoration projects, such as stained glass in Gothic cathedrals or etched glass in Beaux-Arts museums, may require specialized training for handling and precision molding.

3. Regulatory Adaptation:
    - While ASTM, EN, and DIN standards provide broad compatibility, local adaptations may be necessary for seamless adoption across diverse regions.

Nevertheless, these obstacles are manageable through further research and collaborative training programs. By integrating standardized protocols and leveraging automation, fabrication complexities can be mitigated, improving efficiency and adoption rates. The approach also aligns with the UN Sustainable Development Goals (SDG 11: Sustainable Cities), underscoring its relevance in contemporary architectural conservation.

Conclusion

This study demonstrates that the combination of refractory concrete and alkali-activated binders presents a viable and sustainable solution for reproducing ornamental glass elements in historical retrofitting. The proposed system balances thermal resilience, environmental sustainability, and economic feasibility, addressing the inefficiencies of traditional restoration techniques.

Compliance with ASTM, EN, and DIN standards ensures broad applicability, facilitating implementation across different architectural styles and regulatory frameworks. Furthermore, by enabling small-batch production with minimal waste, this innovation enhances accessibility for underfunded heritage projects. Future research will focus on refining fabrication techniques, developing automated mixing systems, and fostering interdisciplinary collaboration between material scientists and restorers.

This dual-material approach has the potential to bridge the gap between industrial efficiency and heritage conservation, ensuring that historical architectural elements can be preserved with greater precision, sustainability, and affordability.

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Towards Structural and Scalable Energy Storage: Building Blocks Based on Cement-based Zinc-ion Hybrid Supercapacitors

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Keywords: structural energy storage, aerated cement mortar, zinc-ion hybrid supercapacitor.

The rapid development of renewable energy systems has exaggerated the imbalance between energy supply and demand, which intensifies the urgency for large-scale, safe and cost-effective energy storage solutions. As the most widely used structure materials worldwide, endowing cement-based materials functions of energy storage can break through the limitations of conventional energy storage systems and provides new usage scenarios from civilian facilities to large-scale engineering. However, the mostly adopted electrodes, working based on electric double layer capacitance and pseudocapacitance, are selected to form supercapacitor, which have problems such as low energy density, no voltage plateau, and high cost. Zinc-ion hybrid capacitors (ZIHCs) represent relatively new systems that combine the Faradaic reaction of zinc anodes with the non-Faradaic adsorption/desorption of cathode capacitors (e.g., active carbon (AC)) to enhance the energy density, power density, and lifespan. Therefore, the integration of ZIHCs with cement-based structures show potential prospects for realizing high performance structural energy storage systems (SESSs) and practical utilization in the future.

The SESS based on ZIHCs was fabricated by sandwiching commercial zinc foil anode, aerated mortar separator and AC cathode. The aerated mortar was prepared by synergistic effect of physical air-entrainer, sodium dodecyl sulfate (SDS), and chemical air-entrainer, aluminium powder (AP). The cylindrical specimens with a radius of 12 mm and a thickness of 5 mm were used for electrochemical testing through electrochemical workstation (CHI 660C, HUACHEN). The 20×20×20 mm cubic specimens were used for compressive strength measurement at a loading rate of 0.5 mm min^{-1}. The Bruker-AXS Discover X-ray diffractometer with the Cu target (wavelength: 1.5406 Å) was used for X-ray diffraction (XRD) analysis. The quantitative analysis of reaction and hydration products was performed by employing a STA 449F5 simultaneous thermal analyzer (STA) with a temperature elevation speed of 10 ℃/min, and the elevated temperature ranged in 30-1000℃. The morphology of the samples was observed using the Quanta 3DFEG field-emission scanning electron microscope (SEM) equipped with an EDX analyzer (Octane Elect Plus). The large-scale pores were visualized using the YXLON PRECISION S X-ray computed tomography (X-CT) while the small-scale pores of samples were detected by the Auto Pore IV 9520 mercury intrusion porosimetry (MIP).

Consequently, for the electrochemical properties, SESS based on ZIHCs, demonstrate exceptional specific energy density (71.4 Wh kg^{-1} at 68.7 W kg^{-1}), high areal energy density (2.0 Wh m^{-2} at 1.9 W m^{-2}), and favorable cycling stability (~92% capacity retention after 1000 cycles). For the mechanical properties, the aerated mortar separator with optimized AP dosage of 0.1 wt% showed low compressive strength (5.4 MPa) and improved compressive strength (15.2 MPa) with high ionic conductivity (13.2 mS cm^{-1}) after soaking in the $ZnSO_4$ electrolyte for 28 days. For the strength enhancing mechanism, when the aerated mortar separators were immerged, a part of $ZnSO_4$ electrolyte reacted with CH from cement hydration and generated $Zn_4SO_4(OH)_6 \cdot 5H_2O$ and gypsum to fill the macro pores, causing a refined pore structure and enhanced mechanical performance. Meanwhile, the other part of $ZnSO_4$ electrolyte fully filled the remaining pores caused by the minus pressure, resulting in a high ionic conductivity.

In conclusion, a high performance SESS was proposed by synergistically combining the most widely used building material, cement mortar, with the extremely safe zinc-ion hybrid supercapacitors. Through air entrainment and leveraging the "adverse reaction" of $ZnSO_4$ electrolyte, aerated cement mortar is

engineered with a multiscale pore structure, exhibiting dual functionality: efficient ionic conductivity as cell separators and robust load-bearing capacity for structure integrity. This new device presents an optimal balance among electrochemical performance, mechanical strength and construction costs, holding the potential to revolutionize energy storage and mitigate the significant CO_2 emissions associated with the entire lifespan of cement and concrete buildings or structures.