

Review

3D Concrete Printing Review: Equipment, Materials, Mix Design, and Properties

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Abstract: 3D concrete printing (3DCP) technology holds significant potential to revolutionise traditional concrete production methods, offering designers and architects greater flexibility in creating intricate and innovative structures. Beyond structural applications, 3D printed concrete products encompass decorative elements, customised design solutions, and even artistic installations. The 3DCP process is highly automated, often integrating building information modelling (BIM) systems, minimising the need for manual labour and generating minimal material waste. 3DCP is regarded as one of the most advanced and efficient methods for fabricating concrete components in the future. This paper examines 3DCP technology and equipment, focusing on the selection of binder types, aggregates, and chemical admixtures, suitable for printable concrete mixes. Particular attention is given to the consistency and workability of 3DCP mixtures. Furthermore, the study evaluates the influence of 3D printing parameters on the mechanical properties of hardened concrete. The insights presented in this review contribute to a deeper understanding of 3D concrete printing technologies, equipment, and materials, benefiting researchers, structural engineers, and designers in the pursuit of enhanced durability and performance of 3D printed concrete structures.

Keywords: 3D concrete printing (3DCP); printed concrete; concrete mix; contour crafting; D-shape technology; air-entraining agent; geopolymers



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1. Introduction

3D concrete printing (3DP) is an additive manufacturing technology based on the layer-by-layer deposition of a specially designed concrete mixture, without the need for formwork or compaction of the placed material. The practical implementation of 3D printing technology in construction requires an interdisciplinary approach, drawing on the expertise of specialists in robotics, computational design, materials science, and architecture [1].

J. Pegna made the first attempt to apply additive manufacturing technology to cement-based materials in 1997 (USA) [2]. Over the past decade, the development of 3D concrete printing (3DP) has accelerated significantly, accompanied by a growing number of research groups active in this field of construction (Figure 1) [3]. Several pioneering companies have taken early steps in large-scale concrete additive manufacturing, including ICON (Texas, USA), Apis Cor (USA, Russia), XtreeE (France), WinSun (China), CyBe (Netherlands), Mighty Buildings (California, USA), and WASP (Italy) [4].

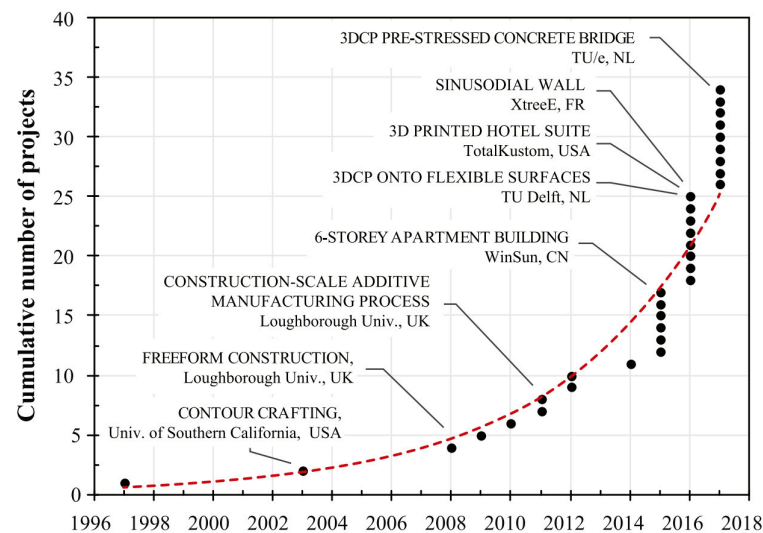


Figure 1. The rise in additive manufacturing since 1997 [3].

According to forecasts, 3DCP is a promising technology that could significantly reduce construction waste (~30–60%), labour costs (~50–80%), and production time (~50–70%) [1]. However, contrasting views also exist. G. De Schutter et al. noted that while 3DCP offers various opportunities to lower economic costs compared to traditional construction methods, some uncertainty remains, particularly regarding its environmental impact [5].

Nonetheless, it is widely believed that 3DCP will enable the rapid construction of sustainable and affordable housing, especially in low-income regions of the world, facilitate the creation of complex designs, support repair and reconstruction efforts, and even allow for building structures on the Moon or Mars [1].

Several impressive projects have already been realised worldwide. In 2014, the Chinese company WinSun presented a five-storey 3D printed apartment building and 1100 sq. meters villa. 3D printed elements were produced off-site and assembled on-site [6].

In December 2015, the company AMT SPECALIA (Yaroslavl, Russia) printed a house of 298.5 m² area in one month (Figure 2) [7]. Apis Cor Company printed a house in the Moscow region (Russia) in 24 h [8]. The examples of the first 3D printed commercial buildings were presented in the Southern Hemisphere (Figure 3) [9] and United Arab Emirates [10].



Figure 2. Printed house by a company AMT SPECALIA [7]: (a) printing process; (b) final product.

In addition to the printing of houses and commercial buildings, 3D printing technology has also been applied to the production of infrastructure elements, such as bridges (Figure 4a), bus stops, and a fountain restoration (Figure 4b) [11–13].



Figure 3. The first 3D printed commercial building in Hamilton (New Zealand) [9].



Figure 4. 3D printed infrastructure elements: (a) the first 3D printed bridge in Madrid (Spain) [11]; (b) restoration of the fountain in Palekh (Russia) [13].

3DCP was also used in the production of architectural forms of different functionality (Figure 5) [14]. Digital fabrication has opened for architecture unexpected new possibilities for previously unachievable materiality, detail, and complexity, but deeper findings into a holistic perspective of the 3D printing technologies as factors, which can influence architecture, are missed [15,16].



Figure 5. Concrete choreography at the Origen Festival of Culture (Switzerland). Photo by Benjamin Hofer [14].

The intensive development of 3DCP in the construction industry is continuing nowadays. The American company SQ4D offered the first 3D printed houses holding the certificates of occupancy in Riverhead, New York [17]. Texas Military Department's Joint Force Headquarters in Austin is another example [18]. An affordable 3D printed neighbourhood for poor families was built in Mexico [19]. A company "Kamp C" (Belgium) built a two-storey house of 90 sq. metres in situ (Figure 6), rather than assembling it from pre-printed elements [20]. Developers in Southern California offer 30 beautifully designed zero net energy 3D printed single-family homes in Rancho Mirage [21]. Cazza Technologies, a pioneer in exploring large-scale 3D printing, has plans to build the world's first 3D printed skyscraper using a "crane printing" technique [22].

Despite the remarkable interest in 3DCP and examples of the successful application of this technology, certain limitations still hinder its widespread adoption. Challenges relate to the properties of fresh concrete, including the open time, setting behaviour, layer cycle time, deformation control, rheological characteristics, and workability. In the hardened state, key issues involve anisotropic mechanical properties, interlayer bond strength, bulk density variations, underfilling, shrinkage, tensile reinforcement, durability, and the standardisation of testing the properties of hardened concrete. Dimensional stability also presents difficulties, such as achieving minimum printable dimensions and tolerances, ensuring the appropriate density, optimising hatching strategies, modelling and simulating the printing process, and producing overhanging structures [3,23]. Also, there are challenges of upscaling 3DCP to larger buildings and the limited number of printing methods available, each requiring specifically engineered concrete mix designs [23].



Figure 6. Two-storey 3D house in Belgium. Photo by "Kamp C" and Jasmien Smets [20].

2. 3D Concrete Printing Settings and Equipment

2.1. Main Phases of 3D Concrete Printing Process

The 3D concrete printing process can be divided into two main phases: delivery and deposition. In the delivery phase, the concrete mixture is prepared for 3D printing and delivered through the hose to the nozzle. In the deposition phase, the materials are extruded through the moving nozzle onto the surface of a supporting platform or previously printed layers. The delivery phase can be linked with off-line or in-line mixing, which determines further properties of the 3D printed concrete.

The key equipment in the delivery phase is the pump (piston pump, peristaltic squeeze pump, or screw pump), while in the deposition phase, the core equipment is an end effector which controls the movement of the nozzle. For a successful 3D printing process,

the concrete mixture must have suitable pumpability for delivery and buildability for deposition [24]. The 3D concrete printing system layout is shown in Figure 7 [25].

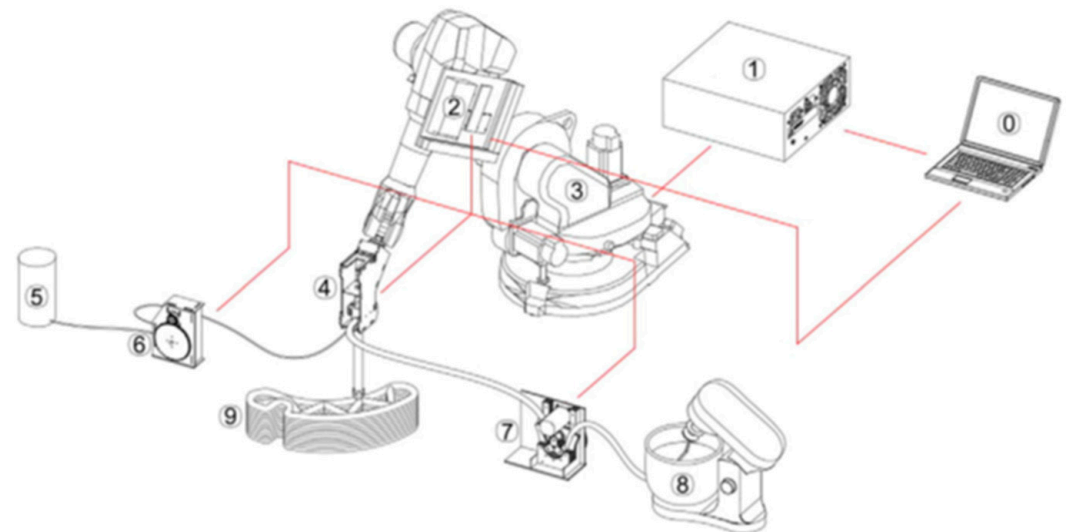


Figure 7. Schematic diagram of a 3D concrete printing system. The system includes the system command unit (0) coordinating the robot controller (1) and printing controller (2); a robotic arm (3) handling the printhead (4); separate peristaltic pumps delivering the accelerating agent (6) and premix material (7); a premix mixer (8); and the 3D printed object produced by the process (9) [25].

At present, contour crafting, concrete printing, and D-shape technologies represent the most intensively researched approaches within the domain of 3D concrete printing.

2.2. Contour Crafting (CC)

CC is a gantry-based 3D cementitious material printing system (Figure 8) for large-scale applications developed by B. Khoshnevis [24,26].

The 3D mixture is extruded through the nozzle, which forms the perimeter of the designed structure. The layers are formed when the nozzle returns to the original position and forms a closed loop. The nozzle then rises and starts printing the next layer atop the previous one. With CC technology, a permanent 3D formwork of the future 3D printed structure is created [24]. CC is an additive manufacturing technology that uses computer-controlled top and side trowels to create a superior surface finish of the final objects. The concrete mix is extruded to the area bounded by the rim walls [26].

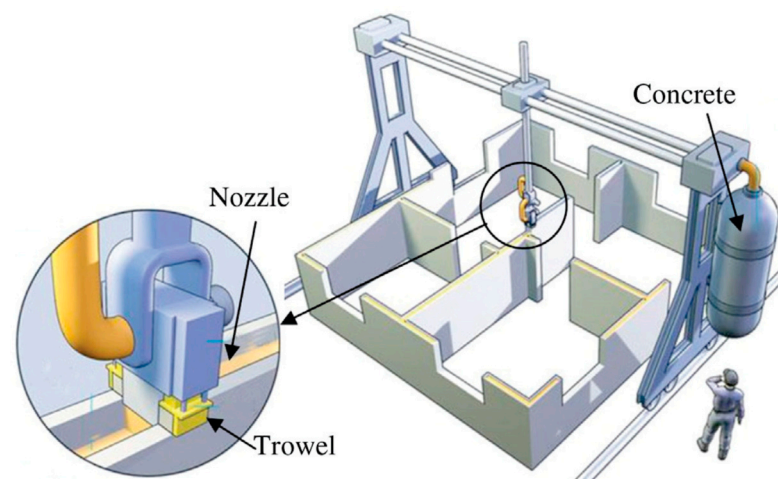


Figure 8. Contour crafting 3D printing system [27].

In the (CC) 3D printing process, construction begins with a digital building model, requiring seamless interoperability between various components of the construction system, and the selected Building Information Modelling (BIM) software platform (Figure 9) [28].

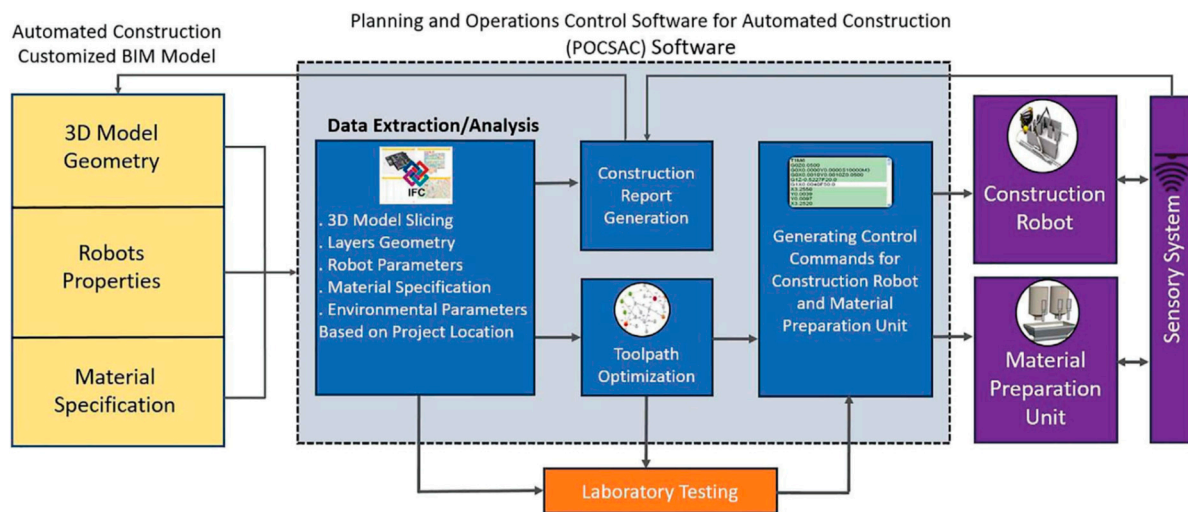


Figure 9. Methodology and framework for operations control software for automated construction [28].

The entire construction workflow in the CC system is driven by the generation of a tool path, which defines the nozzle's position, orientation, velocity, and material deposition rate throughout the building process. This tool path information is then translated into a sequence of machine-specific commands and uploaded to the CC machine. To ensure efficient fabrication of complex structures, researchers focus on the tool path optimisation by developing collision-free strategies, including path cycling, buffer zone path cycling, and auxiliary buffer zones [27].

CC printing technology contributes to better surface quality, higher speed of production, and a choice of materials [26]. However, despite these advantages, CC has several drawbacks, such as vertical extrusion limitations, the complexity of the initial formwork and trowel system, interruption of the sequential casting of concrete due to hydrostatic pressure, insufficient mechanical properties, and poor interfacial performance of the printed layers [25].

Along with the gantry-based system, the arm-based system had started its development (Figure 10). This system differs by the additional print nozzle yaw, pitch, and roll control. The tangential continuity method enables the print nozzle to create more articulate print designs [29]. The robot-based system has a wider variety of designed structures compared to CC. This technology is suitable for onsite printing due to its mounting on the movable platform [24].

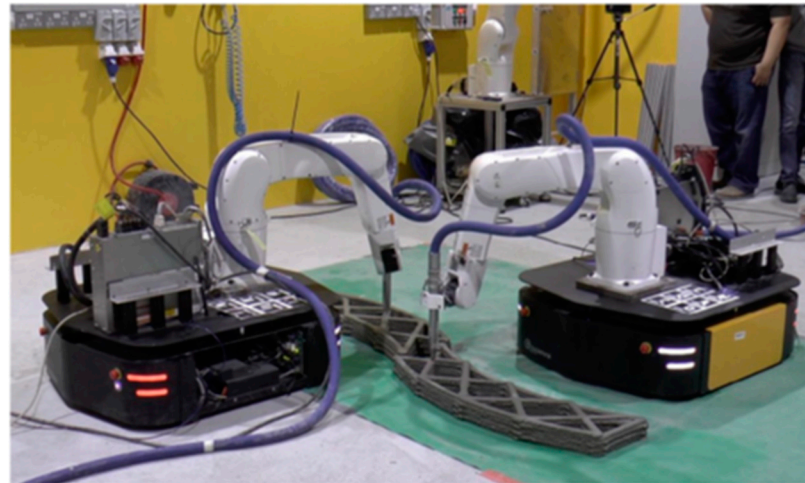


Figure 10. 3D printing by the team of mobile robots [29].

2.3. Concrete Printing (CP)

Similar to the CC system, the CP system (Figure 11) created by Lim et al. [30] is based on the extrusion process of cementitious materials. The main advantages of CP compared CC are better printing system control and higher printing resolution. The absence of surface scraping in CP makes the layered texture of the printed structure visible. Compared to CC technology, the CP printing system creates filaments of smaller dimensions [24].

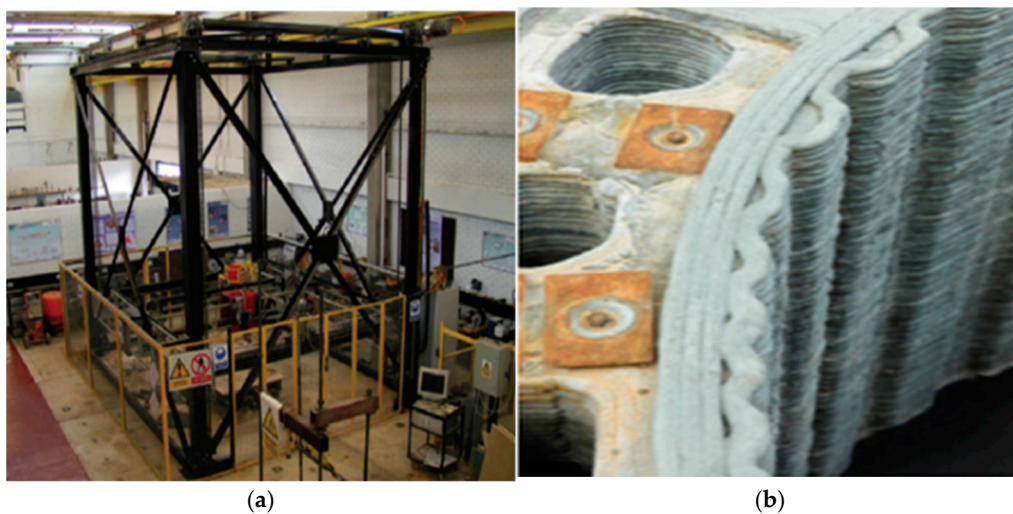


Figure 11. The CP system: (a) gantry framework; (b) details of printed structure [30].

In the (CP) system, the entire geometry of each layer can be printed continuously, rather than beginning with the outer perimeter [1]. The system consists of a large frame equipped with a movable beam and a mounted nozzle. The nozzle travels along the beam, while the beam itself moves in a direction orthogonal to the nozzle's path, enabling free-form 3D printing in the horizontal plane [24]. The raw material is premixed and stored in a pump located outside the printer. It is then fed through a pipe to a small hopper positioned above the nozzle [1].

2.4. D-Shape Printing

Binder jetting, powder bed printing, or D-shape printing technology (Figure 12) was first applied by architect Enrico Dini to create complex elements (with cement binder).

It is based on powder deposition and the bonding of powder with a chemical agent (binder) [1,31,32].

The system consists of a printing head containing a series of nozzles used to dispense the chemical agent and the solid powder. Initially, the powder is dispensed to form a layer of designed thickness. After that, rolling cylinders apply a homogeneous pressure to the powder and the chemical agent is sprayed onto the powder layer in predetermined locations [1]. D-shape printing technology contributes to a high degree of geometric freedom. However, the system has some disadvantages related with reinforcement, the layer height determined by the binding process, recycling of unbound cement powder, and required post-manufacture processing after printing [31,33].

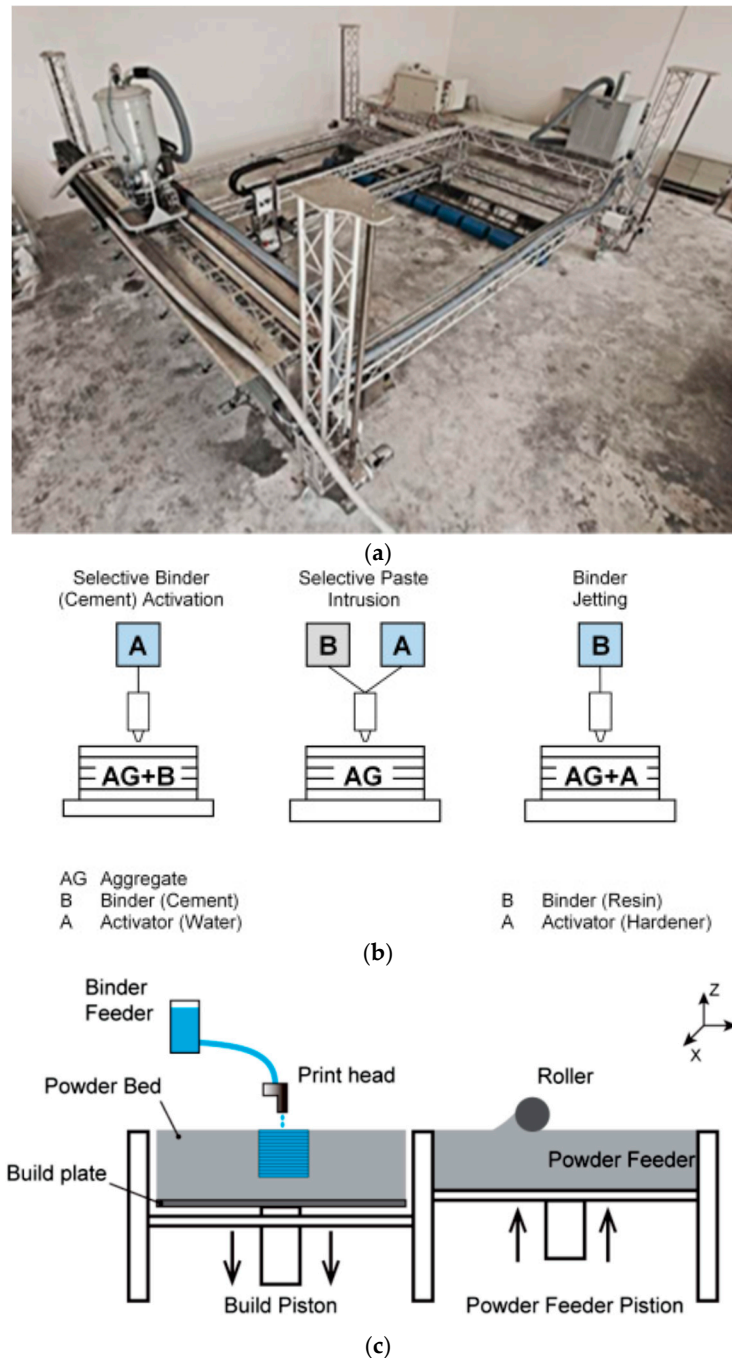


Figure 12. 3D technology: (a) D-shape printer [34], (b) schematic diagram of selective binding particle-bed 3D printing [35]; (c) schematic diagram of powder-based method [36].

2.5. Comparison of 3D Printing Systems

The geometric parameters of the printer limit the large-scale application of 3D printed concrete in construction practice [1]. CP- and D-shape systems are considered as more suitable for off-site printing, while CC is more applicable for producing construction elements in situ [32]. However, the development of 3D printing systems expands the possibilities of applying them both off-site and in situ with local construction materials used [25,34]. The main features of currently available 3D printing systems are compared in Table 1 [1].

Table 1. Comparison of 3D printing systems [1].

Methods	Contour Crafting	Concrete Printing	D-Shape
Printing process	Extruding	Extruding	Spreading
Raw materials	Mortar or cementitious materials	Mixed 3D printed concrete	Powdered materials and chemical agents
Resolution	Smooth surface	4–6 mm	~13 mm
Printing speed	Low	High	Medium
Printing dimension	Large-scale structure	Large-scale structure	Medium-size structure
Advantages	Smooth surface formed by trowels	High strength and building speed	High strength
	Conduits can be embedded into components		
	Intelligent switching of printing materials		
Disadvantages	Slower speed of construction due to trowels	High performance requirements for 3D printed concrete, such as setting and hardening times	Lower resolution
	Low bonding strength between layers caused due to longer intervals		Big quantities of powdered materials required
			Redundant powder materials have to be removed

3. Binder Type and Technical Characteristics

In the context of 3D concrete printing, printable concrete mixtures are often referred to as “inks”, reflecting their function as flowable, extrudable materials that must possess specific rheological properties, such as pumpability, extrudability, and buildability. These properties primarily depend on the type of binder used, which determines the rheological properties of the mixtures and their hydration behaviour, essential for printability and buildability.

Different types of binder materials were proposed for 3D printing. The possibility of using ordinary Portland cement (OPC) of CEM 42.5 R strength class was studied [37–40]. D. Weger and C. Gehlen used CEM 42.5 R cement to print elements using the particle-bed-based method [38]. A. Vespalec et al. analysed 3D printing possibilities using a mix of CEM I 42.5 R cement modified with metakaolin [39]. The concrete mix formulations with CEM I 52.5 R or CEM I 52.5 N cement for 3D concrete printing are presented in other studies [40–43]. Le et al. [40] chose CEM I 52.5 cement to obtain high-performance printed concrete having a compressive strength above 100 MPa and a flexural strength above 10 MPa. The cement CEM I 52.5 content in 3D printing mix formulations studied

varies from $\sim 330 \text{ kg/m}^3$ [41] to $\sim 550\text{--}620 \text{ kg/m}^3$ [42,43], depending on the amounts of supplementary cementitious materials used to replace cement.

The setting parameters are crucial for 3D printing mixture. To control the printability of a 3D mixture, researchers suggest to mix OPC and calcium sulfoaluminate (CSA) cement [44–48]. Khalil et al. developed a printable mix containing 7% CSA and 93% OPC, and reached a compressive strength of the printed samples equal to 79 MPa [44]. Mohan et al. compared the impact of CSA and the OPC-CEM I 52.5 N mix on 3D printable concrete. The researchers found that the mixture based on CSA had a significantly lower open time and a higher plastic viscosity than the OPC-based mixture, whereas the yield stress and the lubricating layer were similar for both types of cement [45]. B. Zareian and B. Khoshnevis noticed that CSA works as a catalyst in the concrete hardening process, and, therefore, contributes to higher early strength development. The researchers tested the binder for a 3D printing mixture based on 60% CSA and 40% type I OPC [46].

Y. Weng et al. proposed a formulation for a sustainable and rapid hardening 3D printing mix based on magnesium potassium phosphate cement (MPC), replaced by a combination of fly ash and silica fume at different rates [49].

Along with mineral binders, geopolymers can be applied as a binder for 3D printing mixture. S. Muthukrishnan et al. investigated a geopolymer based on ground granulated blast furnace slag and fly ash activated by the anhydrous sodium metasilicate (Na_2SiO_3) in a 3D printing mix design [50]. O. Ly et al. compared a geopolymer based on fly ash activated by sodium hydroxide (NaOH) and CEM III/B 32.5 N-S class cement. The researchers produced artificial 3D printed concrete reefs and found that cement was a better binder for this application [51]. The commonly used binders in 3D concrete printing are presented in Table 2.

Table 2. Characteristics of different binders, used in 3D concrete printing [52].

	OPC	CSA	CSA-OPC	Geopolymer	MPC
Characteristics suitable for 3D printing	High strength, high stability	High early strength, short setting time, less impact on the environment	Short setting time, high early strength	High durability, high chemical resistance, eco-friendly	Rapid setting time, high early strength, low shrinkage
Limitations	Long setting time, weak early strength	Low printing open time, high pumping pressure	Reduction in later strength and cracking due to high CSA content	High drying shrinkage, harsh curing conditions	Low printing open time

4. Aggregate Fineness and Optimisation of Particle Size Distribution

The type of aggregates used has a significant impact on the properties of 3D printed concrete. Aggregates determine early-age behaviour, mechanical properties, and shrinkage resistance of concrete [37]. In most cases, the composition of 3D printed concrete includes up to 2 mm fraction sand as a fine aggregate, whereas coarse aggregates are not used in a 3D printed concrete mix design [40,41,43–45,53]. Le et al. used up to 2 mm sand with a sand/binder ratio of 60:40 and water/cement ratio of 0.37 for a printer with a nozzle diameter of 9 mm [40]. Calcareous crushed 0/2 mm sand with 19% of particles smaller than 63 μm in the mixture with an OPC/sand ratio of about 1.2, and a W/C ratio of about 0.35 was suggested for a 3D concrete mixture in the study [44]. Concrete compositions with a binder-to-sand ratios of 1:1.5 and 1:2 and water-to-binder ratios of 0.3 and 0.37 were proposed in the studies [41] and [43], respectively, where sand with a maximum grain size

of 2 mm was used as a fine aggregate. Mohan et al. applied sand with a nominal size of 2 mm and specific gravity of 2.65 g/cm^3 and varied aggregate-to-binder ratios from 1.0 to 1.8 to reduce the binder content. The researchers observed that the increase in aggregate content leads to an increase in yield stress, viscosity, and pumping pressure of a 3D printed concrete mixture [54]. Kazemian et al. tested 3D concrete, in which artificial sand with a nominal maximum aggregate size of 2.36 mm, specific gravity of 2.6 g/cm^3 , fineness modulus of 2.9, and absorption capacity of 1.3% was used as a fine aggregate [55].

Zhang et al. used three types of sand as fine aggregates: 0/4.75 mm natural sand with a 2.61 fineness modulus, 0/1.18 mm fine sand with a 2.02 fineness modulus screened from natural sand through a 1.18 mm square hole sieve, and 0/2.36 mm sand with a 2.33 fineness modulus screened from natural sand through a 2.36 mm square hole sieve. The researchers noticed a linear relationship between the flowability of cement paste and the optimum aggregate content in a printable mortar with a given buildability. The flowability and rheological properties of cement pastes containing sand with different aggregate sizes were tested in the study (Figures 13 and 14) [56].



Figure 13. Buildability assessment of 3D printed concrete with sand of different fineness [56].

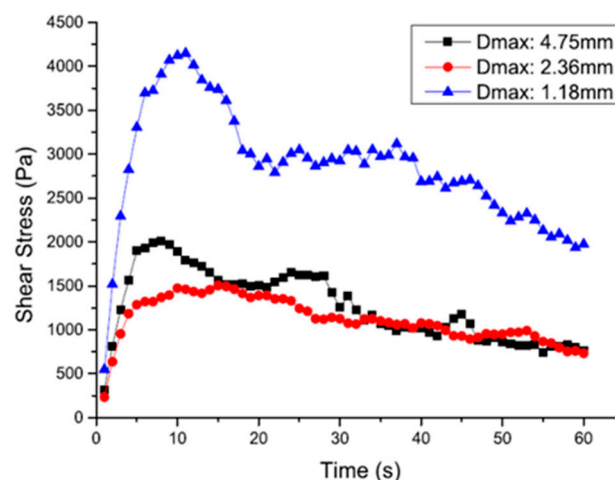


Figure 14. Results of rheological tests on mortars with different sand fineness (tests with a constant shear rate of 0.2 s^{-1}) [56].

Rigid surface aggregates with maximum sizes of $3/32''$, $3/16''$, $1/4''$, and $1/2''$ and different aggregate-to-cement ratios varying from 1.1 to 2.75 were researched [46]. The researchers identified the increase in the compressive strength of the mixtures with smaller-size aggregates and explained it by the decrease in aggregate volume relative to the total composite volume.

In other studies, a 3D printed concrete mixture was designed using sand with a maximum grain size of 4 mm [39,42]. Meurer and Classen used sand with a maximum grain size of 4 mm and the aggregate ratio of 25%, 30%, 25%, and 20% for the sieve fractions of 0.0–0.2, 0.2–1.0, 1.0–2.0, and 2.0–4.0, respectively. The researchers highlighted that only a

small portion of the aggregate with 2–4 mm grains can ensure a dense structure and a good buildability [42].

A study [39] demonstrated the applicability of fine and coarse aggregate combinations in a 3D printed concrete mix design. The mortar was extruded using a specially designed extruder at a constant speed of 10 mm/s in a horizontal direction. 0–4 mm sand was chosen as a fine aggregate, and 4–8 mm crushed stone was used as a coarse aggregate. The concrete mixture was prepared with a water-to-binder ratio of 0.57, and the binder–fine–coarse aggregate ratio was approximately 1:2.26:0.6 [39]. Rahul and Santhanam evaluated the 3D printability of concrete prepared with lightweight expanded clay aggregates with a maximum size of 10 mm. The concrete mixture was extruded from a piston pump-based 3D printer system. Concrete mixtures with quartz sand as fine aggregates were also studied. The binder-to-aggregate ratio was 60:40 for all tested samples [57].

The 3D printed concrete mix design should also meet sustainability requirements. Therefore, the origin of the aggregates for concrete should be considered, and the possibilities of using different types of waste materials as a replacement for traditional aggregates in 3D printed concrete compositions should be investigated.

Bai et al. investigated the application of desert sand (small size), river sediment sand (medium size), and recycled concrete (large size) as aggregates in the development of eco-friendly 3D concrete composition. In the course of research, it was observed that desert sand has more uniform gradation, with more than 90% of the grains smaller than 0.20 mm and a maximum sand grain diameter of 0.30 mm, whereas the river-sediment sand has spherical shape grains and more than 50% and 90% of the grains are smaller than 2.3 and 4.0 mm, respectively. Recycled concrete aggregate was of a cuboid shape and had a maximum particle size of up to 1/3 of the printing nozzle diameter to avoid blockage of the printing nozzle. The researchers highlighted that the interlayer distribution and skeleton of the graded aggregate contribute to improving the interfacial interlocking capacity and contact bonding between layers. Also, the mitigation of shrinkage of the cement matrix was observed with the addition of aggregates due to the reduction in cementitious material content in the concrete mixture [37]. Ly et al. tested compositions with recycled sand (limestone sand, glass sand, and seashell sand) mixed with geopolymers or cement for 3D printing of artificial reefs [51]. Ting et al. applied recycled glass in a 3D printed concrete mix design. The researchers compared 3D printed concrete formulations with recycled glass and with river sand. The recycled glass of medium, fine, and super fine grading with particle size ranges of 1000–1700, 500–1000, and 150–710 μm , respectively, was tested. The recycled glass-based mixture demonstrated better flow behaviour but lower mechanical properties compared to the river sand-based mixture [58].

5. Control of Bonding Parameters with Chemical Admixtures

Chemical admixtures, such as superplasticisers (SPs), viscosity-modifying agents (VMAs), setting retarders (SRs), and accelerators (SAs), are important components in a 3D printed concrete mix design. The properties of 3D concrete mixture, such as workability, adhesion, rigidity, a short setting time, and high early strength, are controlled by the chemical admixtures mentioned above [1].

It is expected that in the course of the 3D printing, the cement suspension with the addition of SP will become more fluid during pumping and recover its shape after printing quickly enough to support the next printed filament. It makes the open time shorter for printing and requires constant concrete feeding. The important aspect in the selection of SP is the length of the filament printing path and the place of printing (on-site or off-site). The rheological properties of concrete mixture usually change during the hydration process; therefore, set retarders are necessary to mitigate the changes and extend the open time

before printing. Set retarders can have a negative impact on buildability, but it is possible to overcome this disadvantage by using retarders together with accelerators. The 3D concrete printing mixture must be consistent after the printing, but it should have a minimum fluidity to be extruded through the nozzle. To achieve it, SP is added in combination with VMAs. VMAs prevent segregation, bleeding, and reduce water evaporation and drying shrinkage. The properties of a 3D printed concrete mixture are also controlled by air-entraining agents (AEAs). AEAs improve workability, reduce the exudation tendency and drying shrinkage, contribute to stability during pumping and extrusion/printing, and preserve the geometric shape of the 3D printed concrete elements [59].

Frequently, a 3D printed concrete mixture includes a complex of chemical admixtures in order to regulate the properties of the mixture in different ways.

Kazemian et al. focused on the workability of a fresh “printing mixture” in terms of print quality, shape stability, and printability window. For this purpose, the concrete mixture was prepared with the addition of a polycarboxylate-based high-range water reducing admixture at 0.05 wt% to achieve the required flowability for the mixtures and viscosity-modifying admixture at 0.11 wt% for anti-washout concrete to ensure the increase in the plastic viscosity and cohesion of printing mixtures when the water to cement ratio was of 0.43 [55].

Manu K. Mohan et al. tested gluconate and borax as retarders in the calcium sulfoaluminate (CSA) cement system. Concrete formulation also included a viscosity-modifying admixture dosed at 0.1% by weight of the binder. Both retarders were added at 0.5% by weight of cement to increase the open time; however, they had different effects on the early-age strength. The researchers stated that gluconate has a more remarkable impact on the early-age compressive strength than borax [45].

K. Manikandan et al. used a polycarbonate-based superplasticizer [60] in combination with silica fume in a 3DPC mixture and noticed SP’s capacity to act as a viscosity-modifying admixture. The tested polycarbonate SP improved yield stress and maintained the required viscosity of a 3D concrete mixture for a long time.

Le et al. developed a composition for high-performance 3D printed concrete. Polycarboxylate-based SP was added into the concrete mixture to lower the water/binder ratio and, consequently, to increase the workability and strength of concrete. A constant flow during printing and sufficient open time were maintained by using a retarder based on amino-tris (methylenephosphonic acid), citric acid, and formaldehyde. SP and SR were dosed at 1% and 0.5% by weight of binder, respectively. The chosen chemical admixtures provided the optimum workability, optimum open time of up to 100 min, and the ability to print many layers with various filament groups [40].

Khalil et al. developed a manually printable mix based on 93% OPC and 7% calcium sulfoaluminate cement with a W/C ratio of 0.35, a sand-to-cement ratio of 2, and of a polyvalent non-chlorated acrylic copolymer superplasticizer added at 0.26% of the total weight of the binder [44].

Zhang et al. studied the dependence of the flowability of a 3D printed concrete mixture on the optimum aggregate content with the addition of polycarboxylate ether SP at 0.8–1.0 wt% of the binder [56]. Polycarboxylate ether SP dosed at 1.5–1.8 wt% was also used in the research on 3D printed concrete properties prepared with underutilised or waste solids [37].

Chen et al. designed a composition for 3D printed concrete, which involved a polycarboxylate ether-based SP and a hydroxypropyl methylcellulose-based viscosity-modifying admixture dosed at 2 wt% and 0.14–0.48 wt%, respectively. The researchers stated that the composition with 0.24% VMA produced a small extrusion pressure at different ages or under different extrusion rates and good shape stability after 25 min [41].

3D printed concrete implies the application of new approaches in concrete technology, and is primarily linked with a concrete mix design. It is reasonable to develop new chemical admixtures and complex admixtures to achieve concrete mixtures with new properties. For instance, Salman et al. [61] described the possibility of grafting polycarboxylate ether molecules onto the surface of nano-cellulosic fibres, which can improve extrudability and the hardened properties of 3D printed concrete.

6. Mineral Additives and Micro-Fillers

In addition to chemical admixtures, the properties of 3D printable concrete mixtures can be tuned by various mineral additives [24].

Kazemian et al. [55] investigated four different 3D printable concrete mixtures containing densified silica fume, highly purified attapulgite (nano clay) with an average particle length of 1.75 mm, and polypropylene fibers for shrinkage reinforcement. They observed that modifying the fresh mixtures with silica fume and nano clay enhanced shape stability, whereas no significant improvement was recorded when adding fibres [55].

The effectiveness of clay addition in improving 3D printable concrete mixture properties was reported in [59]. According to that study, the water adsorption capacity of clay leads to increases in viscosity, initial yield stress, plasticity, and flowability of the mixture during printing. Clay's plasticity and moldability are attributed to its sheet-like silicate structure and variable amounts of entrapped water [59].

Mineral additives are frequently used as partial cement replacements in 3D printable concrete mixtures. Limestone is one of the widely used Supplementary Materials. Mohan et al. [45] replaced calcium sulfoaluminate (CSA) cement with limestone powder and found that this substitution significantly reduced the plastic viscosity and, consequently, required a lowered pressure to pump the mixture. The limestone replacement did not alter the rheological properties of the lubricating layer and slightly extended the dormant period. Furthermore, the CSA cement–limestone blend enabled higher print heights compared to OPC-based mixtures, thereby improving the buildability of the 3D printed concrete.

Le et al. [40] investigated concrete modified with fly ash and silica fume. The researchers found the optimal mix to consist of 70% cement, 20% fly ash, and 10% silica fume. Zhang et al. [56] studied a concrete mixture containing silica fume, nanosilica, and micro-sized attapulgite clay to increase the yield stress of the mixture.

Ly et al. [51] compared the 3D printing results of cementitious concrete based on CEM III/B 32.5 N-SR and modified with fly ash and kaolin with geopolymer-modified concrete. The cementitious concrete exhibited superior mechanical properties compared to the geopolymer-modified concrete [51].

A comprehensive investigation into the effects of supplementary cementitious materials (SCMs) on the structural build-up of cement-based materials for 3D printing is presented in [62]. The authors examined mixtures containing various SCMs, including fly ash, silica powder, rice husk ash, and metakaolin. They determined that the particle density and surface potential of these SCMs govern their impact on the structural build-up behaviour of 3D printed concrete.

Yuan et al. [63] studied how mineral admixtures impact the development of the cement paste matrix. They examined additives such as blast ground slag, fly ash, silica fume, nanosilica, nano calcium carbonate, and attapulgite. The research results showed that granulated blast furnace slag and nanosilica were the most effective in accelerating the structural build-up rate.

A summary of the influence of mineral additives on the rheology and buildability of 3D mixtures is presented in Table 3.

Table 3. The influence of mineral additives on rheology and buildability of 3D concrete mixtures.

Reference	[55,56,62]	[51,62]	[45]	[63]	[62]	[56,59]
Material	Silica fume	Fly ash	Limestone	Blast furnace slag	Metakaolin	Clay
Effect on viscosity	Reduced	Reduced	Reduced	Reduced	Increased	Increased
Effect on yield stress	Increased	Reduced	Increased	Reduced	Increased	Increased
Effect on workability	Reduced	Enhanced	Reduced	Enhanced	Reduced	Reduced
Effect on buildability	Enhanced	Reduced	Increased	Reduced	Enhanced	Enhanced
Effect on green strength	Enhanced	Increased	Reduced	Reduced	Increased	Enhanced

7. Fiber-Reinforced Plastics

Steel corrosion is the main factor causing the deterioration of reinforced concrete structures [64,65]. It is recognised that the higher porosity of concrete negatively affects the durability of steel bars. A layered structure increases the porosity of 3D printed concrete and thus reduces the suitability of steel bars for use in 3D printed concrete structures [66–68]. Various reinforcement methods have been proposed and applied to 3D printed concrete. Polymers represent one of multiple 3D printed concrete reinforcement techniques. Fibre-reinforced polymer (FRP), a promising alternative to steel reinforcement, is characterised by its excellent anti-corrosion performance, low cost, ease of use, fatigue resistance, high strength-to-weight ratio, and good electromagnetic properties. FRP is a promising alternative to steel reinforcement in both conventional steel-reinforced concrete structures and 3D printed concrete structures [69–74]. Yan et al. applied FRP reinforcement in 3D printed concrete [75]. Feng et al. proposed using FRP as a reinforcement material for 3D printed concrete columns and beams [76,77]. Sun et al. applied flexible and rigid materials (stainless steel wire, carbon fibre reinforced wire, etc.) to reinforce 3D printed concrete [78]. Other authors proposed an attractive method of using FRP grids as internal reinforcement in 3D printed high-performance concrete structures [79–81]. There are standards and design guidelines governing the application of FRP reinforcement bars in cast concrete; however, little research and information are available on FRP reinforcement in 3D printed concrete structures [82–84]. Flexible FRP grids can be printed simultaneously with 3D concrete [85], but the key issue is the nature of the bond between 3D concrete and FRP reinforcement. The FRP bar bond behaviour in cast concrete, including the stress transfer mechanism and load–slip relationship, has been extensively analysed [86–88]. The unique anisotropic properties of 3D printed concrete can significantly reduce its bonding characteristics with FRP bars [89]. Although FRP reinforcement has been used in 3D concrete, a comprehensive evaluation of FRP and 3D concrete bond performance, with particular attention to anchor length and concrete strength, has not yet been adequately addressed.

8. Consistency and Technological Properties of Fresh Mixture

The properties of concrete in the fresh state are the most important for the performance of 3D printed concrete.

3D printed concrete mixture should be both pumpable and keep its shape with little or no deformation after extrusion. Researchers introduced a list of qualitative descriptors such as pumpability, extrudability, and buildability, specifically for the description of 3D printed concrete in the fresh state [3]. The study of the properties of 3D printed concrete mixture should focus on such aspects as open time (time during which it can be used in the printing process); the influence of open time on pumpability and extrusion; the setting and layer cycle time (the time required to complete one build layer); the influence of the cycle time on the vertical build rate; the deformation of material under the addition of the subsequent

layer; and the rheological parameters of concrete mixture and their applicability for quality control [3].

3D printed concrete mixture should maintain the viscosity and yield stress of the mix, which is critical for the suitable open time during the process. At the same time, the batching process before printing plays a significant role in 3D printing technology. The extrusion of a 3D printed concrete mixture is determined by several factors, such as the shape (round or rectangular) and size of the extrusion nozzle, nozzle movement, and its position in relation to the previous layer. The length of the extrusion path and the speed of the mixture placement define the production time of the printed component and the time needed to overlay the layers and provide a suitable interlayer bond strength [3].

Researchers offer different approaches to test the rheological properties of the mixture for 3D printing. Along with rotational and oscillatory rheological methods, hand-held rotational rheometer, ultrasonic pulse velocity, and penetrometer tests are used as novel techniques in 3D printed concrete mixtures. New testing methods are required to measure high yield stress and the plastic viscosity of 3D printed mixtures [3].

A. Kazemian et al. [55] noticed three main workability aspects for 3D printed concrete mixtures, such as print quality, shape stability, and printability window. The proposed testing procedures were mainly focused on the properties of the printed layer rather than the mixture pumpability or extrusion mechanism. The researchers evaluated the 3D printed concrete mixture as acceptable when it met the following requirements: absence of surface defects of the printed layers, visible and squared layer edges, proper dimension conformity, and dimension consistency. In addition, authors proposed two tests for laboratory testing—layer settlement and cylinder stability—to evaluate the shape stability of 3D printed concrete.

M.K. Mohan et al. investigated the rheological properties and buildability of a 3D printed concrete mixture based on calcium sulfoaluminate cement. The researchers identified that the modified mixture had a shorter open time and higher plastic viscosity than the OPC-based mixture. However, the mixture based on calcium sulfoaluminate cement in combination with limestone showed better buildability compared to the reference OPC-based mixture. Buildability was evaluated according to the critical failure height during the printing [45].

Zhang et al. [56] focused on identifying the relationship between the flowability of the paste, the optimum sand content, and sand fineness. The researchers evaluated the mixture properties basing on the Murata model, the build-up theory proposed by Perrot et al., the yield stress relationship between mortar and cement paste, the relationship between the flowability and yield stress of the cement paste, and stated that the buildability of 3D printed concrete depends on the yield stress of the mortar. From the test results, the authors established a linear relationship between the flowability of cement paste and the optimum aggregate content for the 3D printable mixture of given buildability.

Jacquet et al. noticed that the extrusion of 3D printable concrete is performed through two strategies. The first of them consists of the massive acceleration of material to ensure the stability of the structure, and the second one assumes the usage of firm mortar, which is able to sustain its own weight. At the same time, researchers highlighted that the extrusion-based printing process requires the analysis of the rheological behaviour not only under the stress but also under compression and tension [63]. In the course of the research [90], Jacquet et al. investigated the fresh properties of paste and mortar under shear, compression, and tension, and described the transition between the ductile fluid materials with symmetry in tension and compression and brittle (firm) materials with asymmetry in tension and compression.

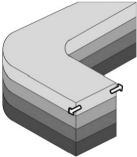
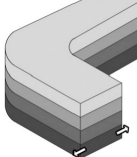
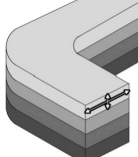
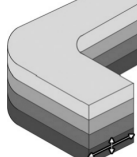
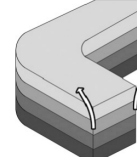
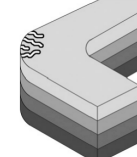
N. Roussel [91] developed the requirements for printable concrete in terms of the yield stress, viscosity, elastic modulus, critical strain, and structuration rate. The rheological requirements are listed in Table 4.

Rahul et al. noticed the importance of the stability and homogeneity of the extrusion of cementitious materials. The researchers offer the parameter “desorptivity” to evaluate the water retaining capability of cement mortar at different constant pressures. In the course of the research, the index based on the desorptivity measurements was obtained for extrudable mixtures [92].

The research [93] describes the application of active rheology control using vibration to make 3D printed concrete flowable during pumping and set immediately after layer deposition. Moreover, J.G. Sanjayan et al. stated that in terms of buildability, the vibration–extrusion gives a similar failure height compared to the non-vibrated extrusion.

In work [94], Zhang et al. investigated the properties of fresh 3D printed concrete and evaluated its buildability, rheological properties (viscosity, yield stress, and thixotropy), workability, green strength, open time, and hydration heat. The researchers modified the mix with clay and silica fume and found that the buildability of this concrete containing a small quantity of nano clay or silica fume increased by 150% and 117%, respectively. At the same time, the remarkable enhancement of the thixotropy and green strength was observed. The buildability of 3D printed concrete was optimised by doubling the content of nano clay and silica fume.

Table 4. Rheological requirements for 3D printable concrete as a function of input printing parameters [91].

Printing Requirement	Individual Strength-Based Layer Stability	Collective Strength-Based Layer Stability	Individual Layer Geometry Control	Collective Geometry Control	Collective Buckling Failure	Plastic Cracking
Illustration						
Input printing process parameters	Layer thickness h_0	Total height H	Layer thickness h_0	Total height H	Total height H layer width δ	Radius of curvature and layer width

Moeini et al. considered the effectiveness of different rheometric methods to evaluate the structuration of the mortar mixtures used for the 3D printing process [95]. The researchers noticed different rheometric methods applied for the evaluation of the build-up of the cement-based mixtures such as the static yield stress evolution, which involves the measurement of static yield stress at various time intervals after the mixing; the small amplitude oscillatory shear method, which assesses the evolution of the storage modulus and the loss modulus with time; and the hysteresis loop (re-building energy) method, which consists of the determination of the ascending and the descending flow curves. Along with rheometric methods, the authors listed the non-rheometric approaches, including the penetration resistance, undisturbed mini-slump spread loss, and the inclined plate testing method, which can be applied for the evaluation of build-up. Based on these methods, it is possible to derive the value of yield stress of the tested concrete mixture.

To sum up the results of the above-mentioned studies, the properties of 3D printable fresh concrete are determined by the open and cycle time, extrudability, pumpability,

buildability, setting parameters of the mixture, and deformations during the placement of the following layers. The rheological properties also play an important role in managing the properties of the 3D printable concrete mixture. The development of new testing methods for the 3D printable concrete mixture is required due to its differences from traditional concrete.

9. Properties of 3D Printed Concrete

The main feature of the 3D printed concrete in the hardened state is its anisotropy. The properties of 3D printed concrete in the hardened state requires to take into account such aspects as layer adhesion, bulk density, under-filling, tensile reinforcement, shrinkage, durability, and the methodology of the testing of the hardened properties [3].

T.T. Le et al. studied the hardened properties of a high-performance fibre-reinforced fine aggregate concrete extruded through a 9 mm diameter nozzle. The researchers determined the density, compressive strength, flexural strength, tensile bond strength, and drying shrinkage of 3D printed concrete. In the course of the research, it was established that well-printed concrete has a density of 2350 kg/m³, compressive strength of 75–102 MPa, flexural strength of 6–17 MPa, depending on the testing direction, and tensile bond strength between layers varying from 2.3 to 0.7 MPa [40].

Bai et al. investigated the influence of the particle grading characteristics on the printability-related early-age behaviours, mechanical properties, and shrinkage resistance. The research showed that the interlayer distribution and skeleton of the gradated aggregate contribute to improving the interfacial interlocking effect and contact bonding between layers. Moreover, the authors stated that the addition of aggregates contributes to the mitigation of the cement matrix shrinkage due to the reduction in the cementitious material content [37].

The research [96] focused on the evaluation of the effect of interlocking on bond strength between the layers of the contour-crafted structure. In the course of the research, it was observed that bonding strength is sensitive to interlocking.

Wolfs et al. studied the relation between 3D printing process parameters and the bond strength of 3D printed concrete. The impact of the parameters, such as the interlayer interval time, nozzle height, and surface dehydration on compressive and tensile strength was evaluated. The researchers stated that with the increase in the interlayer interval time, the bond strength between layers reduced. Moreover, they highlighted the need for the standardisation of the test methods of 3D printed concrete in terms of the materials used and process parameters [97].

Ye et al. developed a novel ultra-high ductile concrete containing polyethylene fibre for 3D printing technology. The researchers conducted mechanical tests in different directions to evaluate the mechanical anisotropy of the studied concrete. The specimen printed from the fibre-modified concrete mixture demonstrated 1.5% higher mechanical performance [98].

Ding et al. evaluated the flexural properties of 3D printed concrete, which included recycled sand and fibre [99]. The test of the concrete samples in different directions (Figure 15) revealed that flexural stiffness decreased by 15–20% after the addition of 50% of recycled sand, while the negative impact of the recycled sand on the flexural strength was compensated by the presence of the fibre.

Authors also assessed the early age mechanical properties of 3D printable materials. In the course of the research, it was established that low stiffness causes elastic deformation, while a lack of green strength leads to plastic failure or brittle failure in older age specimens [99]. They applied small amounts of nano clays to improve the early age properties.

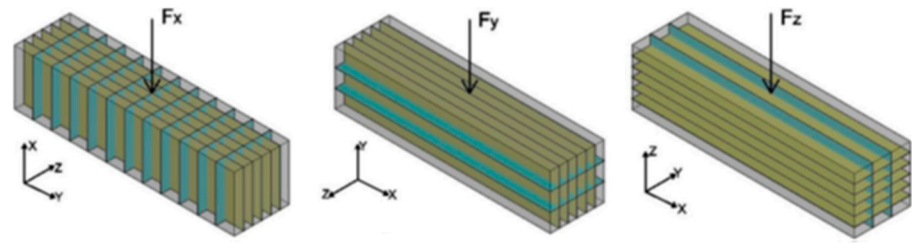


Figure 15. Layer and loading orientations of the 3D printed specimens [99].

Xiao et al. considered the impact of the nozzle dimensions, interfacial bond strength, and concrete properties on the compressive and flexural strengths. This study revealed that the horizontal shear deformation between printed filaments leads to the strength reduction in 3D printed specimens under compression. Moreover, the compressive strength is relatively lower while the flexural strength is much higher in the specimens loaded in the Y and Z directions [100].

K. Cuevas et al. developed 3D printable lightweight concrete by replacing natural aggregates with waste glass at 50% and 100%. The researchers reported an improvement in the flexural and compressive strength of the composite when 50% of the cement was replaced with waste glass. However, a 100% replacement resulted in a slight reduction in mechanical performance [101].

A summary of the influence of different raw materials on the performance in 3D printing is presented in Table 5.

Table 5. The influence of different raw materials on the performance in 3D printing.

Raw Materials	References		Pros	Cons
Binders	[3,37,97,99–101]	Ordinary Portland cement	Widely available, predictable performance, good early strength	High CO ₂ footprint, moderate shrinkage
	[40]	Ordinary Portland cement (high strength)	Achieves high compressive strength, good early age strength	High content increases shrinkage, high CO ₂ emissions
	[98]	UHPC	High strength and durability	Expensive
	[3]	Geopolymer	Low carbon, good buildability, reduced shrinkage	Less standardized, variable strength development
Mineral additives	[3,40,99]	Fly ash	Improves durability, workability, and pumpability, reduces heat and shrinkage, long-term strength gain, reduces CO ₂	Slower strength gain, reduced early age strength
	[3,40,98]	Silica fume	Increases compressive and flexural strength, reduces permeability, porosity, and shrinkage	Expensive, increases water demand, can affect workability, requires more superplasticizer
	[3]	Slag	Improves buildability, reduces shrinkage	May reduce early strength depending on proportion

Table 5. Cont.

Raw Materials	References		Pros	Cons
Aggregates	[3,40,97,100]	Natural fine sand	Stable rheology, good flowability and strength, suitable for extrusion, smooth surface finish	Higher density, limited contribution to strength, neutral sustainability impact, weaker mechanical bond, potential for nozzle clogging
	[3,37]	Lightweight aggregates	Reduces density, enhances insulation	Reduces strength, increases shrinkage
	[3,37,101]	Recycled waste aggregates	Lightweight, eco-friendly, cost-effective, promotes circular economy	Variable quality, lower mechanical performance, higher shrinkage, inconsistent printability
		Expanded microspheres	Thermal insulation	Lower strength, higher shrinkage
Reinforcement	[3]	Steel fibers	Greatly improves tensile and flexural strength, controls cracking	Difficult to extrude, may clog nozzle
	[3]	Polymeric fibers	Enhance ductility, improve green strength	Can reduce flowability, may lead to anisotropy in printed layers
	[40]	Polypropylene microfibers	Reduces plastic shrinkage, enhances green strength	Slight workability reduction if not dispersed well
	[98]	Polyethylene fibers	Improved ductility, reduced cracks	Difficult to mix evenly
Chemical admixtures	[3,37,40,97–101]	Superplasticizers	Improve flowability, workability, and strength, enhanced interlayer adhesion, improved pumpability and print quality	Expensive, risk of segregation and delay in early strength development, require precise control, complicated mix design
	[3,40]	Retarders	Extend open time, allow for longer print sessions	Can delay setting and reduce early strength and buildability
	[3]	Accelerators	Improve buildability, allow faster layer stacking	May reduce open time, harder to control in varying temperatures

In summary, the evaluation of 3D printed concrete in the hardened state should consider key properties such as bulk density, interlayer bonding strength, shrinkage, durability, compressive strength, and tensile strength. Furthermore, there is a pressing need to develop standardised testing methods tailored to the specific characteristics of 3D printable concrete and the parameters of the printing process.

10. Sustainability and Future Trends of 3D Printed Concrete

The conventional construction of engineering structures involves different stages, such as planning and design, selection of suitable materials and their transportation, assembly of structural elements, etc.). These are labour-intensive activities, which typically give

rise to such issues as occupational safety risks, budget overruns, and project delays [102]. Despite its substantial contribution to the global economy, with projected expenditures reaching USD 14 trillion by 2025, the construction industry continues to lag behind other sectors in terms of technological advancement, productivity, and the adoption of automation and robotics [103]. Research [104] conducted in Central and Northern Europe shows that the biggest incentive for companies to invest in 3D printing technologies is related only to the possibility of increasing automation to address the shortage of skilled labour in the construction sector, rather than environmental benefits. The adoption of 3D printing technologies in the construction industry has the potential to facilitate the production of complex structures with exceptional precision and speed, thereby conserving natural resources, reducing pollution, and lowering labour costs [102,105]. As shown by recent studies [106], beyond its economic advantages, 3D printing technology also holds significant potential for reducing the environmental impact of construction. It contributes to lowering the global warming potential, smog formation, eutrophication, acidification, and fossil fuel consumption. Although the research on the recycling potential of 3D printed structures at the end of their service life is scarce, existing technological solutions already demonstrate considerable potential for the reuse of demolition waste. This reuse capability also supports reductions in the overall environmental footprint [107].

Moreover, 3D printing technologies have notable potential to limit emissions of greenhouse gases throughout the cement supply chain, from the production of printable mixtures to their application in newly built structures. Researchers [108] have compiled a list of production strategies focused on 3D printable mixtures and their application in structural elements, accompanied by detailed policy recommendations aimed at optimising the mitigation of climate-related impacts. These strategies and associated policy guidelines are summarised in Table 6.

Table 6. Strategy for comparing 3D printable cementitious mixtures across five policy areas [108].

Policy Area	Advanced C3DP Manufacturing Strategy	Climate-Optimized C3DP Strategy
Research and development	Continue funding studies related to material compositions and printing protocols that improve the strength, durability, and long-term performance of 3D printed structures.	Increase funding for the development of low-carbon 3D printable cementitious mixtures.
		Fund studies that improve knowledge of structural design optimisation to reduce material use and waste with C3DP.
Information dissemination and workforce development	Establish open-source data repositories for industry and academia to share data on reliable materials' manufacturing and printing protocols.	Encourage reporting and sharing of data on LCA studies, GHG inventories, and other environmental metrics within the open-source repositories.
	Commission demonstration projects with long-term performance testing plans to increase trust and the uptake of C3DP in construction projects.	Conduct environmental assessments and LCA studies in the demonstration projects to test and showcase the environmental impact of C3DP compared to conventional construction.
		Encourage construction firms to carry out GHG inventories and share data in open-source repositories.
	Establish training programs to produce skilled workers with knowledge of C3DP materials and processes.	Upskill the workforce by integrating courses on sustainability and the environmental impacts of C3DP into training programs.

Table 6. Cont.

Policy Area	Advanced C3DP Manufacturing Strategy	Climate-Optimized C3DP Strategy
Standards and codes	Develop manufacturing standards to ensure the strength and durability of 3D printable cementitious materials.	Include guidelines in the standards for low-carbon 3D printable cementitious mixtures containing materials like slag, fly ash, clay, and geopolymers.
	Update building codes to include safe, replicable, and low-cost 3D printing protocols.	Consider designing emission product standards for the materials. Integrate design optimisation into building codes to encourage an increase in material use efficiency and reduce waste. Include GHG inventories for printable cementitious materials and printing processes in building codes.
Public procurement and partnerships	Commission construction projects employing C3DP in publicly funded construction to increase demand.	Drive innovation by prioritising the use of low-carbon 3D printable cementitious mixtures and design optimisation in the publicly funded C3DP projects.
	Establish public–private partnerships with construction firms to increase uptake of C3DP construction.	Encourage construction firms to use low-carbon 3D printable cementitious mixtures and design optimization in their projects.
Financial and structural incentives	Offer loans and rebates to conventional cement and concrete producers manufacturing 3D printable cementitious mixtures to increase material supply and reduce costs.	Offer additional grants to producers of low-carbon printable cementitious mixtures.
	Offer financial and structural incentives to construction firms to increase the uptake of C3DP in construction projects.	Award tax credits, rebates, and building permits to C3DP construction projects with sustainability objectives such as reduced material use, formwork, and waste.
Overview of the manufacturing strategies that target the production of 3D printable cementitious mixtures. For each of the five policy areas identified, we recommend strategies for using C3DP in construction to bolster climate mitigation and to incorporate greenhouse gas emissions criteria in the technology from the outset.		

Global warming potential is a commonly used metric to quantify the environmental impact of 3D printing technologies. It measures the total emissions of greenhouse gases (primarily carbon dioxide (CO₂) and methane (CH₄)) generated during the production process, expressed in terms of carbon dioxide equivalent (CO₂-e) [52]. Recent advances in 3D printing technology have led to the development of concrete mixtures with reduced cement content by incorporating low-carbon Supplementary Materials, such as recycled glass [109], fly ash [110], various types of slag [111–113], silica fume [114–116], and metakaolin [117,118].

Geopolymers are amorphous ceramic systems produced from widely available raw materials [119]. It has been estimated that the production of 1 kg of geopolymer releases nearly five times less CO₂ compared to Portland cement manufacturing [120]. Geopolymers were first applied in 3D printing in 2016. In recent years, a growing body of significant research [119–122] has focused on adapting alternative binders to replace cement in 3D printing technologies. These developments indicate that the rapid advancement of cement-free 3D printed structures may soon become a reality. However, the sustainability and industrial viability of geopolymers, both economically and environmentally, are currently limited by the high cost of alkaline activators, such as sodium silicate (Na₂SiO₃) and sodium

hydroxide (NaOH) [121]. Cost-effective and environmentally friendly alternatives to conventional alkaline activators must be explored with the aim of expanding the application of geopolymers in 3D printing technologies and securing a share of the construction industry market [122].

Several directions for the development of 3D printing technologies are envisioned. Current building regulations do not yet cover large-scale 3D printing applications in construction and the absence of a normative framework presents significant barriers to a practical implementation of 3D printing in construction. Achieving a breakthrough in 3D printing technologies will require research to focus on the critical review, harmonisation, and reformulation of design principles and standards. This effort should support the development of design guidelines, calculation methodologies, and construction techniques specifically tailored to 3D printed structures [123].

The automation of 3D printing processes and their integration with artificial intelligence could fundamentally transform conventional construction practices, enabling autonomous and adaptive building systems [102]. Further investigation is also needed into topological optimisation strategies [124], which offer opportunities to refine the internal structure of 3D printed components and enhance resource efficiency.

Substantial advances in printing hardware, raw materials, structural systems, and design methodologies are expected to lead to the next technological milestone—4D printing [123]. This emerging technology, inspired by the fascinating process of spider silk spinning, enables printed structures to change shape and function in response to external stimuli [125].

11. Conclusions

1. The concrete 3D printing process can be realised with the application of the contour crafting, concrete printing, and D-shape printing methods. Each of these methods has advantages and disadvantages which should be taken into account in relation to the type of 3D printed structural element.
2. Cement CEM I 42.5 (52.5) N (R), calcium sulfoaluminate cement can be applied as a binder material for 3D printed concrete.
3. The 3D printed concrete mixture is mainly prepared using only fine aggregates, and 0/2 mm fraction sand is most widely used as the fine aggregate. However, some research demonstrates the possibility of applying 0/4 mm fraction sand, and even coarse aggregates (crushed stone) of 4/8 mm fraction for 3D printed concrete.
4. Chemical admixtures such as superplasticisers, viscosity-modifying agents, setting retarders, and accelerators are used to manage by the workability, adhesion, rigidity to print high-rise structures without failure, short setting time, and high early strength of 3D printed concrete.
5. Silica fume, ground slag, fly ash, and attapulgite can be used as mineral additives, including nano additives such as nano calcium carbonate, nanosilica, and nano clay.
6. The terms “pumpability”, “extrudability”, and “buildability” were introduced for the characterisation of 3D printable concrete in a fresh state. The fresh properties of 3D printable concrete involve the evaluation of such parameters as the open and cycle time, deformation of the material after the addition of the subsequent layer, and rheological properties of the concrete mixture.
7. 3D printable concrete is characterised by the anisotropy in the hardened state. The properties of hardened 3D printable concrete should be considered concerning the layer adhesion, bulk density, under-filling, tensile reinforcement, shrinkage, and durability.

8. The development of 3D printed concrete technology requires the creation of specific methodologies for the testing of concrete properties in fresh and hardened states due to the differences of this concrete in comparison with traditional ones.

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References

1. Zhang, J.; Wang, J.; Dong, S.; Yu, X.; Han, B. A review of the current progress and application of 3D printed concrete. *Compos. Part A* **2019**, *125*, 105533. [CrossRef]
2. Pegna, J. Exploratory investigation of solid freeform construction. *Autom. Constr.* **1997**, *5*, 427–437. [CrossRef]
3. Buswell, R.A.; Leal de Silva, W.R.; Jones, S.Z.; Dirrenberger, J. 3D printing using concrete extrusion: A roadmap for research. *Cem. Concr. Res.* **2018**, *112*, 37–49. [CrossRef]
4. Craftcloud. Available online: <https://all3dp.com/2/2019-best-companies-building-3d-printed-houses/> (accessed on 24 March 2025).
5. Schutter, G.D.; Lesag, K.; Mechtcherine, V.; Nerella, V.N.; Habert, G.; Agusti-Juan, I. Vision of 3D printing with concrete—Technical, economic and environmental potentials. *Cem. Concr. Res.* **2018**, *112*, 25–36. [CrossRef]
6. Shanghai-Based WinSun 3D Prints 6-Story Apartment Building and an Incredible Home. Available online: <https://3dprint.com/38144/3d-printed-apartment-building/> (accessed on 24 March 2025).
7. The First 3D-Printed Residential Building in Europe Was Presented in Yaroslavl. Available online: <https://specavia.pro/articles/pervyj-v-evrope-zhiloj-dom-napechatannyj-na-3d-printere-predstavili-v-yaroslavle/> (accessed on 19 May 2025).
8. 3D Printed House by Apis Cor Entirely Created in One Day. Available online: <https://www.arch2o.com/3d-printed-house-apis-cor/> (accessed on 24 March 2025).
9. First 3D Printed Commercial Building in Southern Hemisphere Completed. Available online: <https://qorox.co.nz/news-and-media/first-3d-printed-commercial-building-in-southern-hemisphere-completed/> (accessed on 24 March 2025).
10. 3D Printed Office Building Unveiled in Dubai. Available online: <https://all3dp.com/3d-printed-office-building/> (accessed on 24 March 2025).
11. 3D Printed Bridge. Available online: <https://iaac.net/projects/3d-printed-bridge-development/> (accessed on 3 June 2025).
12. Winsun Uses Recycled Material to 3D Print Sustainable Bus Stop in China. Available online: <https://3dprint.com/198751/winsun-3d-printed-bus-stop/> (accessed on 24 March 2025).
13. The Main Fountain of Palekh Was Printed on a 3D Printer. Available online: <https://specavia.pro/articles/glavnyj-fontan-palexa-napechatali-na-3d-printere/> (accessed on 18 May 2025).
14. Anton, A.; Bedarf, P.; Yoo, A.; Dillenburger, B.; Reiter, L.; Wangler, T.; Flatt, R.J.; Burry, J.; Sabin, J.; Sheil, B.; et al. Concrete choreography: Prefabrication of 3D-printed columns. In *Fabricate 2020: Making Resilient Architecture*; UCL Press: London, UK, 2020; pp. 286–293.
15. XtreeE Prints Concrete 3D Printed Benches with Complex Patterns. Available online: <https://www.3dnatives.com/en/xtreee-concrete-bench-3d-printed-benches-patterns-140920184/#!> (accessed on 24 March 2025).
16. Žujović, M.; Obradović, R.; Rakonjac, I.; Milošević, J. 3D printing technologies in architectural design and construction: A systematic literature review. *Buildings* **2022**, *12*, 1319. [CrossRef]
17. A 3D Printed House Is for Sale in New York. Builders Say It Will Cut Housing Construction Costs. Available online: <https://edition.cnn.com/2021/02/07/us/3d-printed-house-united-states-for-sale-trnd/index.html> (accessed on 24 March 2025).

18. First 3D-Printed Structure to Receive Approval from a Historical Commission—Camp Mabry Innovation Center in Austin, TX. Available online: <https://www.iconbuild.com/newsroom/first-3d-printed-structure-to-receive-approval-from-a-historical-commission-camp-mabry-innovation-center-in-austin-tx> (accessed on 18 May 2025).
19. World's 1st 3D Printed Neighborhood Being Built in Mexico. Available online: <https://www.wbur.org/hereandnow/2020/02/06/worlds-first-3d-printed-neighborhood-mexico> (accessed on 24 March 2025).
20. A Belgian Company Says Its the First Ever to 3D-Print a 2-Story House in One Piece in a Breakthrough for Sustainable Design—See Inside. Available online: <https://www.businessinsider.com/kamp-c-3d-printed-two-story-house-in-belgium-2020-8> (accessed on 24 March 2025).
21. The First 3D-Printed Housing Community in the US is Being Built in the California Desert. Available online: <https://edition.cnn.com/2021/03/18/business/california-3d-printed-neighborhood-trnd/index.html> (accessed on 24 March 2025).
22. Cazza to Build World's First 3D Printed Skyscraper. Available online: <https://www.constructionweekonline.com/article-43436-cazza-to-build-worlds-first-3d-printed-skyscraper/> (accessed on 24 March 2025).
23. Ngo, T.D.; Kashania, A.; Imbalzano, G.; Nguyen, K.T.Q.; Hui, D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos. Part B Eng.* **2018**, *143*, 172–196. [CrossRef]
24. Lu, B.; Weng, Y.; Li, M.; Qian, Y.; Leong, K.F.; Tan, M.J.; Qian, S. A systematical review of 3D printable cementitious materials. *Constr. Build. Mater.* **2019**, *207*, 477–490. [CrossRef]
25. Gosselin, C.; Duballet, R.; Roux, P.; Gaudillière, N.; Dirrenberger, J.; Morel, P. Large-scale 3D printing of ultra-high performance concrete—A new processing route for architects and builders. *Mater. Des.* **2016**, *100*, 102–109. [CrossRef]
26. Khoshnevis, B. Automated construction by contour crafting—Related robotics and information technologies. *Autom. Constr.* **2004**, *13*, 5–19. [CrossRef]
27. Zhang, J.; Khoshnevis, B. Optimal machine operation planning for construction by Contour Crafting. *Autom. Constr.* **2013**, *29*, 50–67. [CrossRef]
28. Davtalab, O.; Kazemian, A.; Khoshnevis, B. Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. *Autom. Constr.* **2018**, *89*, 13–23. [CrossRef]
29. Zhang, X.; Li, M.; Lim, J.H.; Weng, Y.; Tay, Y.W.D.; Pham, H.; Pham, Q.C. Large-scale 3D printing by a team of mobile robots. *Autom. Constr.* **2018**, *95*, 98–106. [CrossRef]
30. Lim, S.; Buswell, R.A.; Le, T.T.; Wackrow, R.; Austin, S.A.; Gibb, A.G.F.; Thorpe, T. Development of a viable Concrete Printing process. In Proceedings of the 28th International Symposium on Automation and Robotics in Construction (ISARC 2011), Seoul, Republic of Korea, 29 June–2 July 2011; pp. 665–670.
31. Wangler, T.; Lloret, E.; Reiter, L.; Hack, N.; Gramazio, F.; Kohler, M.; Bernhard, M.; Dillenburger, B.; Buchli, J.; Roussel, N.; et al. Digital concrete: Opportunities and challenges. *RILEM Tech. Lett.* **2016**, *1*, 67–75. [CrossRef]
32. Shakor, P.; Sanjayan, J.; Nazari, A.; Nejadi, S. Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing. *Constr. Build. Mater.* **2017**, *138*, 398–409. [CrossRef]
33. Wangler, T.; Roussel, N.; Bos, F.P.; Salet, T.A.M.; Flatt, R.J. Digital concrete: A review. *Cem. Concr. Res.* **2019**, *123*, 105780. [CrossRef]
34. Cesaretti, G.; Dini, E.; Kesteliev, X.D.; Colla, V.; Pambaguian, L. Building components for an outpost on the Lunar soil by means of a novel 3D printing technology. *Acta Astronaut.* **2014**, *93*, 430–450. [CrossRef]
35. Lowke, D.; Dini, E.; Perrot, A.; Weger, D.; Gehlen, C.; Dillenburger, B. Particle-bed 3D printing in concrete construction—Possibilities and challenges. *Cem. Concr. Res.* **2018**, *112*, 50–65. [CrossRef]
36. Nematollahi, B.; Xia, M.; Sanjayan, J. Current Progress of 3D Concrete Printing Technologies. In Proceedings of the 34th International Symposium on Automation and Robotics in Construction (ISARC 2017), Taipei, Taiwan, 28 June–1 July 2017; pp. 260–267.
37. Bai, G.; Wang, L.; Ma, G.; Sanjayan, J.; Bai, M. 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates. *Cem. Concr. Compos.* **2021**, *120*, 104037. [CrossRef]
38. Weger, D.; Gehlen, C. Particle-bed binding by selective paste intrusion—Strength and durability of printed fine-grain concrete members. *Materials* **2021**, *14*, 586. [CrossRef]
39. Vespalec, A.; Novák, J.; Kohoutková, A.; Vosynek, P.; Podroužek, J.; Škaroupka, D.; Zikmund, T.; Kaiser, J.; Paloušek, D. Interface behavior and interface tensile strength of a hardened concrete mixture with a coarse aggregate for additive manufacturing. *Materials* **2020**, *13*, 5147. [CrossRef]
40. Le, T.T.; Austin, S.A.; Lim, S.; Buswell, R.A.; Law, R.; Gibb, A.G.F.; Thorpe, T. Hardened properties of high-performance printing concrete. *Cem. Concr. Res.* **2012**, *42*, 558–566. [CrossRef]
41. Chen, Y.; Figueireiro, S.C.; Yalçinkaya, Ç.; Çopuroglu, O.; Veer, F.; Schlangen, E. The effect of viscosity-modifying admixture on the extrudability of limestone and calcined clay-based cementitious material for extrusion-based 3D concrete printing. *Materials* **2019**, *12*, 1374. [CrossRef] [PubMed]
42. Meurer, M.; Classen, M. Mechanical properties of hardened 3D printed concretes and mortars—Development of a consistent experimental characterization strategy. *Materials* **2021**, *14*, 752. [CrossRef]

43. Putten, J.V.D.; Deprez, M.; Cnudde, V.; Schutter, G.D.; Tittelboom, K.V. Microstructural characterization of 3D printed cementitious materials. *Materials* **2019**, *12*, 2993. [\[CrossRef\]](#)
44. Khalil, N.; Aouad, G.; Cheikh, K.E.; Remond, S. Use of calcium sulfoaluminate cements for setting control of 3D-printing mortars. *Constr. Build. Mater.* **2017**, *157*, 382–391. [\[CrossRef\]](#)
45. Mohan, M.K.; Rahul, A.V.; Schutter, G.D.; Tittelboom, K.V. Early age hydration, rheology and pumping characteristics of CSA cement-based 3D printable concrete. *Constr. Build. Mater.* **2021**, *275*, 122136. [\[CrossRef\]](#)
46. Zareian, B.; Khoshnevis, B. Interlayer adhesion and strength of structures in contour crafting—Effects of aggregate size, extrusion rate, and layer thickness. *Autom. Constr.* **2017**, *81*, 112–121. [\[CrossRef\]](#)
47. Soltan, D.G.; Li, V.C. A self-reinforced cementitious composite for building-scale 3D printing. *Cem. Concr. Compos.* **2018**, *90*, 1–13. [\[CrossRef\]](#)
48. Zhu, B.; Pan, J.; Zhou, Z.; Cai, J. Mechanical properties of engineered cementitious composites beams fabricated by extrusion-based 3D printing. *Eng. Struct.* **2021**, *238*, 112201. [\[CrossRef\]](#)
49. Weng, Y.; Ruan, S.; Li, M.; Mo, L.; Unluer, C.; Tan, M.J.; Qian, S. Feasibility study on sustainable magnesium potassium phosphate cement paste for 3D printing. *Constr. Build. Mater.* **2019**, *221*, 595–603. [\[CrossRef\]](#)
50. Muthukrishnan, S.; Ramakrishnan, S.; Sanjayan, J. Effect of alkali reactions on the rheology of one-part 3D printable geopolymer concrete. *Cem. Concr. Compos.* **2021**, *116*, 103899. [\[CrossRef\]](#)
51. Ly, O.; Yoris-Nobile, A.I.; Sebaibi, N.; Blanco-Fernandez, E.; Boutouil, M.; Castro-Fresno, D.; Hall, A.E.; Herbert, R.J.H.; Deboucha, W.; Reis, B.; et al. Optimisation of 3D printed concrete for artificial reefs: Biofouling and mechanical analysis. *Constr. Build. Mater.* **2021**, *272*, 121649. [\[CrossRef\]](#)
52. Wang, C.; Chen, B.; Vo, T.; Rezaia, M. Mechanical anisotropy, rheology and carbon footprint of 3D printable concrete: A review. *J. Build. Eng.* **2023**, *76*, 107309. [\[CrossRef\]](#)
53. Perrot, A.; Jacquet, Y.; Rangeard, D.; Courteille, E.; Sonebi, M. Nailing of layers: A promising way to reinforce concrete 3D printing structures. *Materials* **2020**, *13*, 1518. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Mohan, M.K.; Rahul, A.V.; Van Tittelboom, K.; De Schutter, G. Evaluating the influence of aggregate content on pumpability of 3D printable concrete. In *Second RILEM International Conference on Concrete and Digital Fabrication*; Bos, F., Lucas, S., Wolfs, R., Salet, T., Eds.; Springer: Cham, Switzerland, 2020; Volume 28, pp. 333–341.
55. Kazemian, A.; Yuan, X.; Cochran, E.; Khoshnevis, B. Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. *Constr. Build. Mater.* **2017**, *145*, 639–647. [\[CrossRef\]](#)
56. Zhang, C.; Hou, Z.; Chen, C.; Zhang, Y.; Mechtcherine, V.; Sun, Z. Design of 3D printable concrete based on the relationship between flowability of cement paste and optimum aggregate content. *Cem. Concr. Compos.* **2019**, *104*, 103406. [\[CrossRef\]](#)
57. Rahul, A.V.; Santhanam, M. Evaluating the printability of concretes containing lightweight coarse aggregates. *Cem. Concr. Compos.* **2020**, *109*, 103570. [\[CrossRef\]](#)
58. Ting, G.H.A.; Tay, Y.W.D.; Qian, Y.; Tan, M.J. Utilization of recycled glass for 3D concrete printing: Rheological and mechanical properties. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 994–1003. [\[CrossRef\]](#)
59. Souza, M.T.; Ferreira, I.M.; Moraes, E.G.; Senff, L.; Oliveira, A.P.N. 3D printed concrete for large-scale buildings: An overview of rheology, printing parameters, chemical admixtures, reinforcements, and economic and environmental prospects. *J. Build. Eng.* **2020**, *32*, 101833. [\[CrossRef\]](#)
60. Manikandan, K.; Wi, K.; Zhang, X.; Wang, K.; Qin, H. Characterizing cement mixtures for concrete 3D printing. *Manuf. Lett.* **2020**, *24*, 33–37. [\[CrossRef\]](#)
61. Salman, N.M.; Ma, G.; Ijaz, N.; Wang, L. Impact of physical and physicochemical properties of supplementary cementitious materials on structural build-up of cement-based pastes. *Constr. Build. Mater.* **2021**, *291*, 123281.
62. Navarrete, I.; Kurama, Y.; Escalona, N.; Lopez, M. Impact of physical and physicochemical properties of supplementary cementitious materials on structural build-up of cement-based pastes. *Cem. Concr. Res.* **2020**, *130*, 105994. [\[CrossRef\]](#)
63. Yuan, Q.; Zhou, D.; Li, B.; Huang, H.; Shi, C. Effect of mineral admixtures on the structural build-up of cement paste. *Constr. Build. Mater.* **2018**, *160*, 117–126. [\[CrossRef\]](#)
64. Zhou, W.; Feng, P.; Lin, H.; Zhou, P. Bond behavior between GFRP bars and coral aggregate concrete. *Compos. Struct.* **2023**, *306*, 116567. [\[CrossRef\]](#)
65. Guo, X.; Jin, Z.; Xiong, C.; Pang, B.; Hou, D.; Li, W. Degradation of mechanical properties and microstructure evolution of basalt-carbon based hybrid FRP bars in real seawater and sea-sand concrete. *Compos. Part B Eng.* **2024**, *271*, 111163. [\[CrossRef\]](#)
66. Liu, Q.; Cheng, S.; Sun, C.; Chen, K.; Li, W.; Tam, V.W.Y. Steel cable bonding in fresh mortar and 3D printed beam flexural behavior. *Autom. Constr.* **2024**, *158*, 105165. [\[CrossRef\]](#)
67. Zhang, Y.; Qiao, H.; Qian, R.; Xue, C.; Feng, Q.; Su, L.; Zhang, Y.; Liu, G.; Du, H. Relationship between water transport behaviour and interlayer voids of 3D printed concrete. *Constr. Build. Mater.* **2022**, *326*, 126731. [\[CrossRef\]](#)

68. Ma, L.; Zhang, Q.; Lombois-Burger, H.; Jia, Z.; Zhang, Z.; Niu, G.; Zhang, Y. Pore structure, internal relative humidity, and fiber orientation of 3D printed concrete with polypropylene fiber and their relation with shrinkage. *J. Build. Eng.* **2022**, *61*, 105250. [\[CrossRef\]](#)
69. Lin, G.; Zeng, J.J.; Li, J.X.; Chen, G.M. Chord axial compressive behavior of hybrid FRP-concrete-steel double-skin tubular member T-joints. *Thin-Walled Struct.* **2024**, *195*, 111535. [\[CrossRef\]](#)
70. Liao, J.J.; Zeng, J.J.; Zheng, Y.; Liu, Y.; Zhuge, Y.; Zhang, L.H. Constitutive models of ultra-high performance concrete (UHPC) under true tri-axial compression and an analysis-oriented model for FRP-confined UHPC. *Eng. Struct.* **2024**, *304*, 117656. [\[CrossRef\]](#)
71. Zhou, J.K.; Hao, Z.H.; Zeng, J.J.; Feng, S.Z.; Liang, Q.J.; Zhao, B.; Feng, R.; Zhuge, Y. Durability assessment of GFRP bars embedded in UHP-ECCs subjected to an accelerated aging environment with sustained loading. *Constr. Build. Mater.* **2024**, *419*, 135364. [\[CrossRef\]](#)
72. Zeng, J.J.; Zeng, W.B.; Zhuge, Y.; Zhou, J.K.; Quach, W.M.; Feng, R. Behavior and modeling of FRP grid-reinforced ultra-high-performance concrete under uniaxial tension. *Struct. Concr.* **2024**, *25*, 1185–1207. [\[CrossRef\]](#)
73. Zeng, J.J.; Xiang, H.Y.; Cai, W.J.; Zhou, J.K.; Zhuge, Y.; Zhu, J.Y. Behavior of large-scale FRP confined square RC columns with UHP-ECC section curvilinearization under eccentric compression. *Eng. Struct.* **2024**, *301*, 117288. [\[CrossRef\]](#)
74. Zeng, J.J.; Hao, Z.H.; Li, J.L.; Zhuge, Y.; Liu, F.; Li, L.J. Durability assessment of hybrid double-skin tubular columns (DSTCs) under simulated marine environments. *Eng. Struct.* **2024**, *301*, 117168. [\[CrossRef\]](#)
75. Yan, Z.T.; Zeng, J.J.; Zhuge, Y.; Liao, J.J.; Zhou, J.K.; Ma, G.W. Compressive behavior of FRP-confined 3D printed ultra-high performance concrete cylinders. *J. Build. Eng.* **2024**, *83*, 108304. [\[CrossRef\]](#)
76. Feng, P.; Meng, X.M.; Chen, J.F.; Ye, L.P. Mechanical properties of structures 3D printed with cementitious powders. *Constr. Build. Mater.* **2015**, *93*, 486–497. [\[CrossRef\]](#)
77. Feng, P.; Meng, X.; Zhang, H. Mechanical behavior of FRP sheets reinforced 3D elements printed with cementitious materials. *Compos. Struct.* **2015**, *134*, 331–342. [\[CrossRef\]](#)
78. Sun, X.Y.; Ye, B.X.; Lin, K.J.; Wang, H.L. Shear performance of 3D printed concrete reinforced with flexible or rigid materials based on direct shear test. *J. Build. Eng.* **2022**, *48*, 103860. [\[CrossRef\]](#)
79. Zeng, J.J.; Pan, B.Z.; Fan, T.H.; Zhuge, Y.; Liu, F.; Li, L.J. Shear behavior of FRP-UHPC tubular beams. *Compos. Struct.* **2023**, *307*, 116576. [\[CrossRef\]](#)
80. Zeng, J.J.; Feng, P.; Dai, J.G.; Zhuge, Y. Development and behavior of novel FRP-UHPC tubular members. *Eng. Struct.* **2022**, *266*, 114540. [\[CrossRef\]](#)
81. Zeng, J.J.; Chen, J.D.; Liao, J.; Chen, W.J.; Zhuge, Y.; Liu, Y. Behavior of ultra-high performance concrete under true tri-axial compression. *Constr. Build. Mater.* **2024**, *411*, 134450. [\[CrossRef\]](#)
82. Liao, J.J.; Yang, K.Y.; Zeng, J.J.; Quach, W.M.; Ye, Y.Y.; Zhang, L.H. Compressive behavior of FRP-confined ultra-high performance concrete (UHPC) in circular columns. *Eng. Struct.* **2021**, *249*, 113246. [\[CrossRef\]](#)
83. Liu, T.Q.; Liu, X.; Feng, P. A comprehensive review on mechanical properties of pultruded FRP composites subjected to long-term environmental effects. *Compos. Part B Eng.* **2020**, *191*, 107958. [\[CrossRef\]](#)
84. Zeng, J.J.; Ye, Y.Y.; Gao, W.Y.; Smith, S.T.; Guo, Y.C. Stress-strain behavior of polyethylene terephthalate fiber-reinforced polymer-confined normal-, high- and ultra high-strength concrete. *J. Build. Eng.* **2020**, *30*, 101243. [\[CrossRef\]](#)
85. Zeng, J.J.; Li, P.L.; Yan, Z.T.; Zhou, J.K.; Quach, W.M.; Zhuge, Y. Behavior of 3D-printed HPC plates with FRP grid reinforcement under bending. *Eng. Struct.* **2023**, *294*, 116578. [\[CrossRef\]](#)
86. Fan, T.H.; Zeng, J.J.; Hu, X.W.; Chen, J.D.; Wu, P.P.; Liu, H.T.; Zhuge, Y. Flexural fatigue behavior of FRP-reinforced UHPC tubular beams. *Eng. Struct.* **2025**, *330*, 119848. [\[CrossRef\]](#)
87. Zhou, L.; Zheng, Y.; Song, G.; Chen, D.; Ye, Y. Identification of the structural damage mechanism of BFRP bars reinforced concrete beams using smart transducers based on time reversal method. *Constr. Build. Mater.* **2019**, *220*, 615–627. [\[CrossRef\]](#)
88. Zeng, J.J.; Su, T.H.; Chen, J.D.; Hu, X.; Ng, C.T.; Zheng, Y.; Quach, W.M.; Zhuge, Y. Novel prefabricated FRP bar reinforced UHPC shells for column strengthening: Development and axial compression tests. *J. Build. Eng.* **2024**, *94*, 109935. [\[CrossRef\]](#)
89. Sun, X.; Gao, C.; Wang, H. Bond performance between BFRP bars and 3D printed concrete. *Constr. Build. Mater.* **2021**, *269*, 121325. [\[CrossRef\]](#)
90. Jacquet, Y.; Perrot, A.; Picandet, V. Assessment of asymmetrical rheological behavior of cementitious material for 3D printing application. *Cem. Concr. Res.* **2021**, *140*, 106305. [\[CrossRef\]](#)
91. Roussel, N. Rheological requirements for printable concretes. *Cem. Concr. Res.* **2018**, *112*, 76–85. [\[CrossRef\]](#)
92. Rahul, A.V.; Sharma, A.; Santhanam, M. A desorptivity-based approach for the assessment of phase separation during extrusion of cementitious materials. *Cem. Concr. Compos.* **2020**, *108*, 103546. [\[CrossRef\]](#)
93. Sanjayan, J.G.; Jayathilakage, R.; Rajeev, P. Vibration induced active rheology control for 3D concrete printing. *Cem. Concr. Res.* **2021**, *140*, 106293. [\[CrossRef\]](#)

94. Zhang, Y.; Zhang, Y.; Liu, G.; Yang, Y.; Wu, M.; Pang, B. Fresh properties of a novel 3D printing concrete ink. *Constr. Build. Mater.* **2018**, *174*, 263–271. [[CrossRef](#)]
95. Moeini, M.A.; Hosseinpour, M.; Yahia, A. Effectiveness of the rheometric methods to evaluate the build-up of cementitious mortars used for 3D printing. *Constr. Build. Mater.* **2020**, *257*, 119551. [[CrossRef](#)]
96. Zareiyan, B.; Khoshnevis, B. Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete. *Autom. Constr.* **2017**, *83*, 212–221. [[CrossRef](#)]
97. Wolfs, R.J.M.; Bos, F.P.; Salet, T.A.M. Hardened properties of 3D printed concrete: The influence of process parameters on interlayer adhesion. *Cem. Concr. Res.* **2019**, *119*, 132–140. [[CrossRef](#)]
98. Ye, J.; Cui, C.; Yu, J.; Yu, K.; Dong, F. Effect of polyethylene fiber content on workability and mechanical-anisotropic properties of 3D printed ultra-high ductile concrete. *Constr. Build. Mater.* **2021**, *281*, 122586. [[CrossRef](#)]
99. Panda, B.; Lim, J.H.; Tan, M.J. Mechanical properties and deformation behaviour of early age concrete in the context of digital construction. *Compos. Part B Eng.* **2019**, *165*, 563–571. [[CrossRef](#)]
100. Xiao, J.; Liu, H.; Ding, T. Finite element analysis on the anisotropic behavior of 3D printed concrete under compression and flexure. *Addit. Manuf.* **2021**, *39*, 101712. [[CrossRef](#)]
101. Cuevas, K.; Chougan, M.; Martin, F.; Ghaffar, S.H.; Stephan, D.; Sikora, P. 3D printable lightweight cementitious composites with incorporated waste glass aggregates and expanded microspheres—Rheological, thermal and mechanical properties. *J. Build. Eng.* **2021**, *44*, 102718. [[CrossRef](#)]
102. Tabassum, T.; Ahmad Mir, A. A review of 3d printing technology-the future of sustainable construction. *Mater. Today Proc.* **2023**, *93*, 408–414. [[CrossRef](#)]
103. Hossain, M.A.; Zhumabekova, A.; Paul, S.C.; Kim, J.R. A review of 3D printing in construction and its impact on the labor market. *Sustainability* **2020**, *12*, 8492. [[CrossRef](#)]
104. Adaloudis, M.; Roca, J.B. Sustainability tradeoffs in the adoption of 3D concrete printing in the construction industry. *J. Clean. Prod.* **2021**, *307*, 127201. [[CrossRef](#)]
105. Dey, D.; Srinivas, D.; Panda, B.; Suraneni, P.; Sitharam, T.G. Use of industrial waste materials for 3D printing of sustainable concrete: A review. *J. Clean. Prod.* **2022**, *340*, 130749. [[CrossRef](#)]
106. Mohammad, M.; Masad, E.; Al-Ghamdi, S.G. 3d concrete printing sustainability: A comparative life cycle assessment of four construction method scenarios. *Buildings* **2020**, *10*, 245. [[CrossRef](#)]
107. Dixit, M.K. 3-D printing in building construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Central Europe Towards Sustainable Building (CESB19), Prague, Czech Republic, 2–4 July 2019; Volume 290, p. 012012.
108. Gangotra, A.; Del Gado, E.; Lewis, J.I. 3D printing has untapped potential for climate mitigation in the cement sector. *Commun. Eng.* **2023**, *2*, 6. [[CrossRef](#)]
109. Liu, J.; Li, S.; Gunasekara, C.; Fox, K.; Tran, P. 3D-printed concrete with recycled glass: Effect of glass gradation on flexural strength and microstructure. *Constr. Build. Mater.* **2022**, *314*, 125561. [[CrossRef](#)]
110. Benam, S.S.; Sandalci, I.; Kara, B.; Bebek, O.; Bundur, Z.B. Improving the 3D printability of high-volume fly ash mixtures through addition of mineral admixtures. In Proceedings of the RILEM Spring Convention and Conference (RSCC 2024), Milan, Italy, 7–12 April 2024; Ferrara, L., Muciaccia, G., di Summa, D., Eds.; Springer: Cham, Switzerland, 2024; Volume 56, pp. 265–273.
111. Li, D.; Cui, X.; Jang, J.-s.; Wang, G. Sustainable application of blast furnace slag in the field of 3D printing: Material configuration and machine optimization. *Sustainability* **2024**, *16*, 4058. [[CrossRef](#)]
112. Beersaerts, G.; Soete, J.; Giels, M.; Eykens, L.; Lucas, S.; Pontikes, Y. 3D printing of an iron-rich slag based hybrid mortar. A durable, sustainable and cost-competitive product? *Cem. Concr. Compos.* **2023**, *144*, 105304. [[CrossRef](#)]
113. Butkute, K.; Vaitkevicius, V.; Sinka, M.; Augonis, A.; Korjakins, A. Influence of carbonated bottom slag granules in 3D concrete printing. *Materials* **2023**, *16*, 4045. [[CrossRef](#)] [[PubMed](#)]
114. Şahin, H.G.; Mardani, A.; Beytekin, H.E. Effect of silica fume utilization on structural build-up, mechanical and dimensional stability performance of fiber-reinforced 3D printable concrete. *Polymers* **2024**, *16*, 556. [[CrossRef](#)] [[PubMed](#)]
115. Salah, H.A.; Mutalib, A.A.; Kaish, A.B.M.A.; Syamsir, A.; Algaifi, H.A. Development of ultra-high-performance silica fume-based mortar incorporating graphene nanoplatelets for 3-dimensional concrete printing application. *Buildings* **2023**, *13*, 1949. [[CrossRef](#)]
116. Liu, Z.; Li, M.; Moo, J.G.S.; Kobayashi, H.; Wong, T.N.; Tan, M.J. Effect of nanostructured silica additives on the extrusion-based 3D concrete printing application. *J. Compos. Sci.* **2023**, *7*, 191. [[CrossRef](#)]
117. Duan, Z.; Li, L.; Yao, Q.; Zou, S.; Singh, A.; Yang, H. Effect of metakaolin on the fresh and hardened properties of 3D printed cementitious composite. *Constr. Build. Mater.* **2022**, *350*, 128808. [[CrossRef](#)]
118. Peng, Y.; Unluer, C. Development of 3D-printed magnesium silicate hydrate cement mixes involving metakaolin as a substitute for silica source. *Virtual Phys. Prototyp.* **2024**, *19*, e2382173. [[CrossRef](#)]
119. Zhong, H.; Zhang, M. 3D printing geopolymers: A review. *Cem. Concr. Compos.* **2022**, *128*, 104455. [[CrossRef](#)]

120. Ricciotti, L.; Apicella, A.; Perrotta, V.; Aversa, R. Geopolymer materials for extrusion-based 3D-printing: A Review. *Polymers* **2023**, *15*, 4688. [[CrossRef](#)]
121. Shilar, F.A.; Ganachari, S.V.; Patil, V.B.; Bhojaraja, B.E.; Khan, T.M.Y.; Almakayeel, N. A review of 3D printing of geopolymer composites for structural and functional applications. *Constr. Build. Mater.* **2023**, *400*, 132869. [[CrossRef](#)]
122. Barve, P.; Bahrami, A.; Shah, S. Geopolymer 3D printing: A comprehensive review on rheological and structural performance assessment, printing process parameters, and microstructure. *Front. Mater.* **2023**, *10*, 1241869. [[CrossRef](#)]
123. Tu, H.; Wei, Z.; Bahrami, A.; Kahla, N.B.; Ahmad, A.; Özkılıç, Y.O. Recent advancements and future trends in 3D concrete printing using waste materials. *Dev. Built Environ.* **2023**, *16*, 100187. [[CrossRef](#)]
124. Bi, M.; Tran, P.; Xia, L.; Ma, G.; Xie, Y.M. Topology optimization for 3D concrete printing with various manufacturing constraints. *Addit. Manuf.* **2022**, *57*, 102982. [[CrossRef](#)]
125. Zuo, Y.; Liu, H. Is the spider a weaving master or a printing expert? *Therm. Sci.* **2022**, *26*, 2471–2475. [[CrossRef](#)]

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