

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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**INFLUENCE OF ADDITIVES
INTENSIFYING FORMATION OF THE
CALCIUM HIDROSILICATES ON
PROPERTIES OF THE FORMING
MIXTURES AND PRODUCTS OF
AUTOCLAVED AERATED CONCRETE**

SUMMARY OF DOCTORAL DISSERTATION

**TECHNOLOGICAL SCIENCES,
MATERIALS ENGINEERING (08T)**



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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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KALCIO HIDROSILIKATŲ
SUSIDARYMĄ INTENSYVINANČIŲ
PRIEDŲ POVEIKIS AUTOKLAVINIO
AKYTOJO BETONO FORMAVIMO
MIŠINIŲ IR PRODUKTŲ SAVYBĖMS

DAKTARO DISERTACIJOS SANTRAUKA

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Introduction

Problem under investigation. Under Construction Products Regulation 305/2011, which replaces the Construction Products Directive 89/106/EEC, one of the seven basic construction requirements is energy saving and retention. In accordance with this requirement, energy consumption for buildings heating must be as low as possible.

Due to constantly tightening requirements for thermal resistance of building envelopes, aerated concrete is widely used in low-rise building construction. Consequently, it increasingly replaces ceramic or silicate bricks.

The main field of application of autoclaved aerated concrete (AAC) products is building envelopes. AAC has many advantageous properties. Widespread natural raw materials, such as lime, quartz sand, Portland cement and water, are used for the production of this concrete. Therefore, this material can be called as environmentally friendly. It is relatively easy to work with AAC products because it is lightweight and easily processed (cut, milled, drilled), is non-flammable and resistant to decay processes.

AAC has sufficient structural, thermal and acoustic properties. Depending on the density ($400\text{--}600\text{ kg/m}^3$), thermal conductivity may vary from $0.080\text{ W/(m}\cdot\text{K)}$ to $0.16\text{ W/(m}\cdot\text{K)}$. AAC is currently used for low-rise residential buildings as structural – thermal insulating material as well as AAC blocks are used as filler for openings of multi-storey frame buildings.

The main strength property of aerated concrete is compressive strength, but it is low. Compressive and flexural strength may be increased by using pozzolanic or fibre additives intensifying the formation of calcium hydrosilicates. In this thesis, SiO_2 microparticles (AS) as a pozzolanic additive and fibrous-milled carbon fibre (AP) as a fibrous additive were used.

The usage of carbon fibre and SiO_2 microparticles as additives for the production of AAC may extend its field of application, i.e. to use the AAC as a heat resistant material (up to $700\text{ }^\circ\text{C}$).

Topicality of work. Hermetically packaged AAC manufactures during the storage and transportation lose up to 30% of their strength due to accumulation of moisture, therefore, it is relevant when additives, which improve the strength properties of AAC, are used. Strengthened aerated concrete may be facilitated and produced as strong thermal insulating material. Some of these additives are SiO_2 microparticles and milled carbon fibre. In order to obtain the above mentioned properties, it is necessary to determine optimal amount of SiO_2 microparticles and milled carbon fibre as well as solve the uniform distribution problem of these additives and Al paste.

AAC with SiO₂ microparticles has not been studied in its all complexity. Therefore, this thesis examines its influence on properties of AAC forming mixtures: consistency, expansion, maximum temperature (for the hydration of binding materials), plasticity strength and concrete properties: micro- and macrostructure, thermal conductivity, water vapour permeability and freeze-thaw resistance. The influence of carbon fibre milled by ball-mill till fine particles was similarly investigated.

Object of research – autoclaved aerated concrete with silica microparticles and milled carbon fibre additives intensifying formation of calcium hydrosilicates.

Aim of work. Investigate influence, in complex manner, of silica microparticles and milled carbon fibre additives on properties of autoclaved aerated concrete forming mixture and specimens.

Tasks of work. To attain the aim of the dissertation, the following tasks should be solved:

1. To determine optimal amount of SiO₂ microparticles and milled carbon fibre.
2. To investigate the influence of SiO₂ microparticles and milled carbon fibre additives on AAC forming mixtures consistency, maximum temperature, the height of expansion, plasticity strength.
3. To determine the influence of above mentioned additives on properties of AAC (density, macro- and microstructure, phasic composition of calcium hydrosilicates, compressive and flexural strength, thermal shrinkage, thermal conductivity, water vapour permeability, freeze-thaw resistance).
4. To prepare technological scheme of production for AAC with additives.

Methods of research. In this thesis, the properties of AAC forming mixtures were determined on the basis of Martinenko and Morozov summarized method. Strength properties of AAC were determined in accordance with the requirements of LST EN 679 and LST EN 1351. Determination of the density was carried out according to LST EN 678. Macrostructure was determined using optical microscope “Motic”, for the analysis of structure images “UTHSCSA Image tool” and “Pixcavator Image Analysis” softwares were used. For the investigation and analysis of microstructure, scanning electron microscope “JSM 6490 LV” and porosimeter “PoroMaster 33” were used. X-Ray investigation was carried out using diffractometer „DRON-7“, thermographic –

derivatograph „Linseis STA PT-1600“, and thermal shrinkage – dilatometer „LINSEIS L76“. Mathematical-statistical methods were applied for the processing of strength properties investigation results. Methods for determination of AAC thermal conductivity, water vapour permeability and freeze-thaw resistance are presented in Lithuanian standards LST EN 1745, LST EN 772-15 and LST EN 15304.

Scientific novelty. The scientific novelty of the study is proved by the following 6 new results in the materials engineering science:

1. AAC with SiO₂ microparticles and milled carbon fibre additives intensifying formation of calcium hydrosilicates is investigated in its all complexity. Optimal amount of above mentioned additives and compositions of forming mixtures are chosen. Uniform distribution of additives in forming mixture is achieved by dispersing additives (with a part of water and surface activating agent) separately from Al paste as well as selecting appropriate mixing mode.
2. The influence of additives on properties of AAC forming mixtures is determined: spreadability, maximum temperature, the height of expansion, plasticity strength.
3. It is determined that SiO₂ microparticles and milled carbon fibre additives strengthen the walls of AAC inter-pores. SiO₂ microparticles, at an early stage, stimulate the formation of C-S-H by the good contact zone with unreacted sand particles during the thermal treatment. Surface of milled carbon fibre particles acts as crystallization centres of calcium hydrosilicates. Therefore, modified AAC has better strength properties and lower thermal shrinkage.
4. Autoclaved aerated concrete structure, using additives, consists of higher content of closed pores, thus the thermal conductivity and water vapour permeability of hardened concrete are lower.
5. By statistical processing of the test results, regression equations are obtained. They may be used for prediction of AAC compressive and flexural strength values when the density is in the range of 400–450 kg/m³.
6. By using above mentioned additives, the AAC with the density of ~450 kg/m³, compressive strength of ~4 MPa, flexural strength of ~2 MPa, thermal conductivity of ~0.1 W/(m·K) and thermal shrinkage of ~1% is obtained.

Practical value of work results. AAC produced with 1.0% of SiO₂ microparticles or 0.1% of milled carbon fibre additive is superior by its physical-mechanical and thermal-technical properties than AAC without additives. Higher

plasticity strength of forming mixture allows to shorten the duration of technological processes. AAC produced with SiO₂ microparticles and milled carbon fibre additives is characterized by lower thermal shrinkage. This ensures its usage as a heat resistant concrete which withstands up to 700 °C.

Defended propositions

1. SiO₂ microparticles and milled carbon fibre additives have an influence on spreadability, maximum temperature, the height of expansion, plasticity strength and macro- and microstructures of AAC.
2. SiO₂ microparticles intensify the hardening of hydrosilicates, and milled carbon fibre additive act as crystallization centres and stimulate the formation of hydrosilicates during autoclave curing. Such modified AAC has better strength properties.

Structure of dissertation. The volume of the work makes 83 pages (without annex), the text contains 13 numbered formulas, 46 illustrations and 5 tables. 129 references were used in the dissertation.

The dissertation consists of introduction, three chapters, summary of results, list of references and list of author's publications on subject of dissertation.

1. Overview researches of autoclaved aerated concrete with additives

Many authors have studied the SiO₂ microparticles additive and how it effects the dense and aerated concretes. References state that SiO₂ microparticles improve the strength properties of concrete products, reduce the spreadability of dense concretes and promote microstructural crystallinity. However, there are only few studies on how this additive effects the properties of AAC. There are no studies about the influence on properties of AAC forming mixtures, structure formation and properties as well as hydrated new formations.

References analysis of AAC reinforced with fibre additives showed that reinforcing additives may be used for low density (450 kg/m³) AAC production. The most important is the fact that fibre additives increase the strength of AAC. AAC is mostly used in wall constructions under long-term load, therefore, the most important property of AAC is compressive strength and accordingly more attention is paid to the upward adjustment of compressive strength. Many sources analyzed mechanically untreated or grated carbon fibre with length of 5 mm. There are no references about how such fibre, if it is

milled to fine particles (1.0–10.0 μm), could change the properties of AAC forming mixtures.

2. Raw materials and research methods of autoclaved aerated concrete with silica microparticles and milled carbon fiber additives

2.1. Raw materials used for investigation. Milled lime CL90 produced by JSC “Naujasis Kalcitas”, as well as Portland cement CEM I 42.5 R produced by SC „Akmenės cementas“ as binding materials, milled quartz sand from JSC “Anykščių kvarcas” as an aggregate, Al paste “Albo Schlenk Deg 4508/70” as gas-forming agent were used. For uniform distribution of additives in AAC forming mixture, surface active agents (SAA) “Ufapore TCO” were used. For the preparation of AAC forming mixtures, the following additives were used: SiO_2 microparticles “RW-Füller” (AS) (Fig. 2.1, a) and milled carbon fibre (AP) (Fig. 2.1, b).

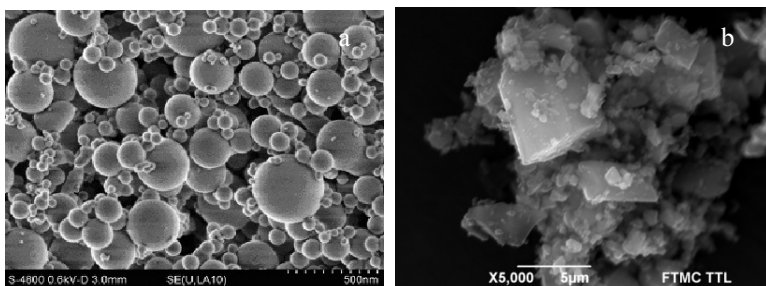


Fig. 2.1. Microstructure of the AS particles (a) and morphology of AP additives milled in dry way (b)

2.2. Preparation of forming mixture and formation of specimens. The temperature of water used was of 20 °C. V/K – 0.54 and it was chosen according to workability of forming mixture. AAC forming mixture components were mixed by vertical mixer (700 turns/min).

2.3. Methods of investigations

Spreadability. To this aim, “Suttard” viscometer was used.

Maximal temperature. After the mixing process of AAC components, forming mixtures were obtained. They were poured to moulds, and their initial temperature and time were measured. The test was conducted until the mixture reached the maximum formation temperature and stopped when the temperature began to fall.

Expansion. The height of forming mixture expansion was recorded every 1 min using mechanical stopwatch with the precision of 1 s and a metal ruler with the precision of 1 mm.

Plasticity strength. Plasticity strength of forming mixtures was determined using “Rebinder” plastometer with a tip angle of 45°.

Ultrasonic impulse velocity (UIV) of forming mixtures. UIV of AAC forming mixtures was determined using “Pundit 7” devices in accordance with LST EN 12504-4. UIV was measured after 20 min of mixture expansion.

Condition of specimens. AAC specimens were conditioned at no higher than 60 °C until their expected absolute humidity had reached (6±2)% of the mass. When the determined humidity was reached, specimens were maintained for at least 2 hours in such conditions that their humidity could not change and the temperature of specimens would be the same as laboratory temperature (20±5) °C.

Macrostructure. The structure investigations were carried out by examining cross-sectional surface of the AAC specimens. Formed specimens were cut, sanded, treated with compressed air from dust. Photo images were taken using Optical microscope “Motic” which magnified 12 times. The flat area of the specimens was examined by “UTHSCSA Image tool” and “Pixcavator Image Analysis” softwares. Pore roundness of the AAC specimen’s cross-section, when a round pore is equal to 100%, as well as the pore perimeter, area, quantity of pores was determined.

Microstructure. AAC specimens matrix contact zone with additives and C-S-H silicate structure was studied using a scanning electron microscope “JEOL JSM-7600F”. Micro pores diameter, volume and area in AAC specimens were determined using mercury pore meter “PoreMaster 33”.

X-ray analysis. Investigations were carried out using X-ray diffractometer “DRON-7”.

Thermographic analysis. Differential Thermographic analysis was performed using derivatograph “Linseis STA PT-1600”.

Density. Density of the AAC specimens was determined in accordance with LST EN 678.

Compressive strength. Compressive strength of the specimens was determined in accordance with LST EN 679.

Flexural strength. Flexural strength of AAC specimens was determined on the basis of LST EN 1351.

Statistical evaluation of experimental results. The mathematical-statistical evaluation of the experimental data was carried out at a confidence level of 95% by determining confidence intervals and by empirical methods for determining

dependencies. Digital regression coefficient values were determined on the basis of the least squares methods.

Thermal shrinkage. Thermal shrinkage of AAC specimens was determined using dilatometer “LINSEIS L76”.

Water vapour permeability. The property of water vapour permeability of AAC specimens were conducted at adjustable temperature control chamber in accordance with method of LST EN 772-15.

Thermal conductivity. Investigation of thermal conductivity of the material was carried out using method of LST EN 1745.

Freeze-thaw resistance. Tests of freeze-thaw resistance were conducted according to LST EN 15304.

3. Research of influence of silica microparticles and milled carbon fiber additives on autoclaved aerated concrete formation mixtures and specimens properties

Good distribution is necessary when adding additives to the AAC forming mixture. To this aim, the AS and AP additive was dispersed with part of the water used (10% of water content), and 0.03% of SAA, and stirred 3 min to completely separate the adhered particles. This resulted in a uniform distribution of AAC forming mixture. Al paste was dispersed as well in order to prevent the adhesion of particles and formation of large pores during the expansion of AAC forming mixture, what can dramatically change the properties of AAC forming mixtures and specimens. Al paste was dispersed with part of the water used as well.

It was found that 1.0% of additive AS decreased the spreadability of AAC forming mixtures by 0.5% but increased the maximum temperature of the mixture during the lime slaking, and height of expansion as well as plasticity strength by: 1.7%, 10.8% and 286%. By adding 0.1% of AP, spreadability, maximum temperature and the height of expansion was reduced respectively by: 1.0%, 2.1% and 10.3% but plasticity strength was significantly increased (by 153%).

Performed macrostructure studies showed that adding a very fine AS (specific surface of $20 \cdot 10^3 \text{ m}^2/\text{kg}$), placing a greater amount of it (1.5%) at constant V/K ratio resulted in an uneven macrostructure. This is evidenced by the reduction of the forming mixture maximum temperature, height of expansion and plasticity strength. Addition of AP additive to the AAC forming mixture did not show visually visible macrostructure changes.

X-ray (Fig. 3.1, a) and thermographic (Fig. 3.1, b) studies showed that the AS additive intensively reacts with lime and promotes the formation of calcium hydrosilicates and better crystallization of tobermorite (Fig. 3.2, b).

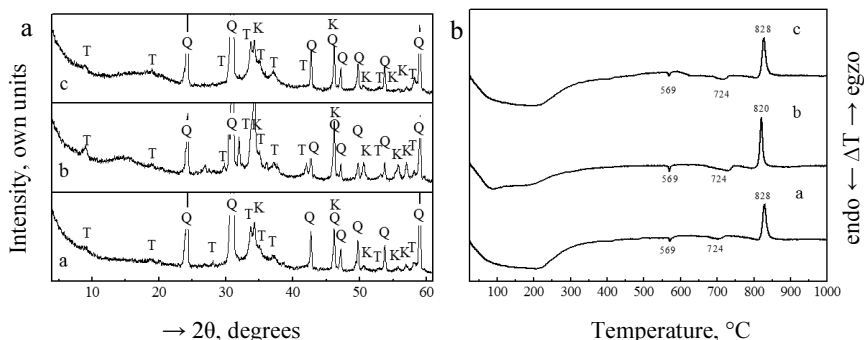


Fig. 3.1. XRD (a) and DTA (b) patterns of AAC specimens at the content of additive by %: a – 0; b – 1.0 AS; c – 0.1 AP. *Q* – quartz; *T* – tobermorite; *K* – calcite

AP additive does not react with the binder, however, the indentations in the AP surface was closely overgrown by hydrosilicates during autoclave curing, and fibre themselves interfere with wall membranes of inter-pores (Figure 3.2, c).

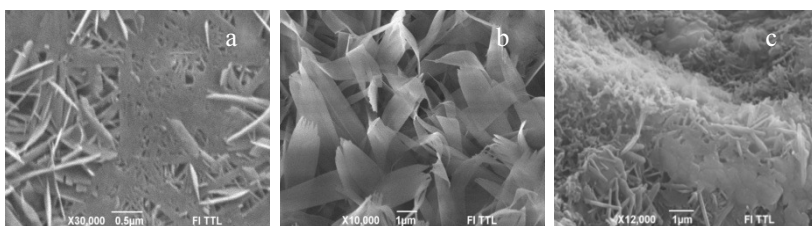


Fig. 3.2. Fragments of surface microstructure of AAC specimens at the content of additive by %: a – 0; b – 1.0 AS; c – 0.1 AP

After the influence of micropores size on their area was determined, it can be stated that at the same volume of micropores and decreased their diameter, the area of micropores increases, and after the influence of micropores size on their volume was determined, it can be stated that reduction of the micropores diameter, increases their volume. During the production of AAC specimens

with AS additive, closed, having small-diameter (1 mm to 0.06 mm), isolated, and evenly distributed pores form.

Using AS additive which amount in a forming mixture was of 0.5%, 1.0%, 1.5%, the highest compressive and flexural strength values were obtained with 1.0% of AS additive. Compressive strength increased by 20%, and flexural strength by 31% in comparison with standard specimen. With 0.1% of AP additive compression and flexural strength of AAC specimens increased by 20% and 8% respectively.

On the basis of obtained results, regression equations were obtained. They may be used for prediction of dotted AAC compressive (Fig. 3.3) and flexural (Fig. 3.4) strength values with desired additive and their amount as follows: AS [0.5–1.5%] (Fig. 3.3 and 3.4, graph a), AP [0.05–0.2%] (Fig. 3.3 and 3.4, graph b), when the density is in the range of [400–450 kg/m³].

$$\sigma_c = (170.3) + (-8.30) \cdot \rho + (19.34) \cdot AS + (0.010) \cdot \rho^2 + (-0.036) \cdot \rho \cdot AS + (-2.05) \cdot AS^2 \quad (3.1)$$

with standard deviation of $S_r=0.0945$, MPa, and determination coefficient of $R^2=0.987$. R^2 shows that 98.7% of AAC compressive strength depends on AS additive amount and density.

$$\sigma_c = (-400.5) + (1.94) \cdot \rho + (-110.2) \cdot AP + (-0.002) \cdot \rho^2 + (0.298) \cdot \rho \cdot AP + (-54.3) \cdot AP^2 \quad (3.2)$$

with standard deviation of $S_r=0.0566$, MPa, and determination coefficient of $R^2=0.9654$. R^2 shows that 96.5% of AAC compressive strength depends on AP additive amount and density.

$$\sigma_b = (374.5) + (-1.83) \cdot \rho + (4.25) \cdot AS + (0.022) \cdot \rho^2 + (-0.008) \cdot \rho \cdot AS + (-0.452) \cdot AS^2 \quad (3.3)$$

with standard deviation of $S_r=0.0109$, MPa, and determination coefficient of $R^2=0.9876$. R^2 shows that 98.8% of AAC flexural strength depends on AS additive amount and density.

$$\sigma_b = (-88.1) + (0.426) \cdot \rho + (-24.2) \cdot AP + (-0.001) \cdot \rho^2 + (0.065) \cdot \rho \cdot AP + (-11.9) \cdot AP^2 \quad (3.4)$$

with standard deviation of $S_r=0.0125$, MPa, and determination coefficient of $R^2=0.9654$. R^2 shows that 96.5% of AAC flexural strength depends on AP additive amount and density.

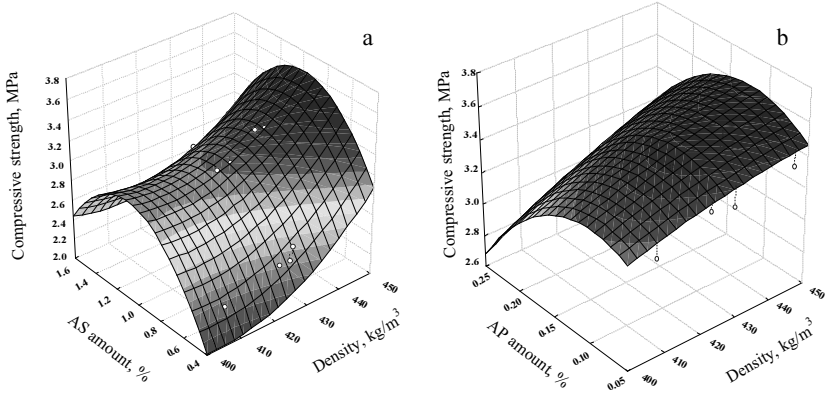


Fig. 3.3. Influence of AS (a) and AP (b) additive and density of AAC on the compressive strength of specimens

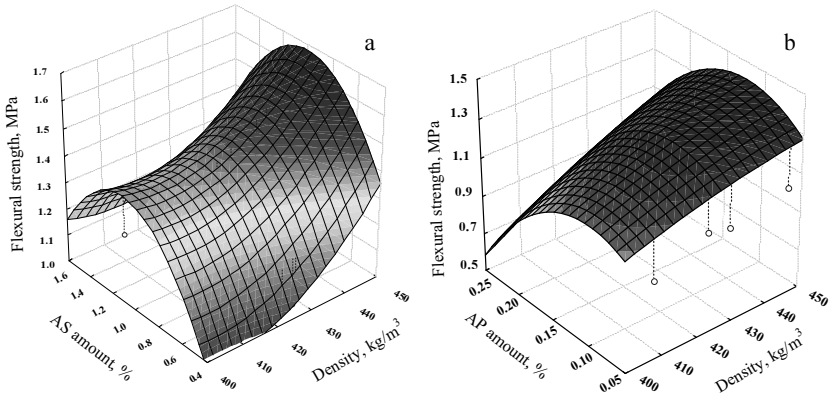


Fig. 3.4. Influence of AS (a) and AP (b) additive and density of AAC on the flexural strength of specimens

Dilatometry studies showed that thermal shrinkage of AAC specimens with AS additive was of 1.24% and it was by 6.8% lower than that of the standard specimen (Fig. 3.5, 2 curve). With AP additive this ratio was 1.12% (Fig. 3.5, 3 curve), i.e. by 16% lower than in the specimen without additives.

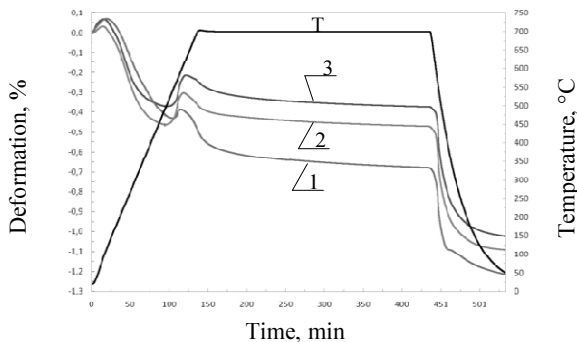


Fig. 3.6. The dilatometric curves of AAC specimens at the following content of additive by %: 1 – 0; 2 – 1.0 AS; 3 – 0.1 AP. T – curve of temperature rising, exposition and lowering

Thermal shrinkage decreased due to denser wall structure of inter-pores and better crystallization of tobermorite. Thermal shrinkage results showed that the modified AAC with AS and AP additives can be used for structures, requiring greater heat resistance (up to 700 °C) of the products.

General conclusions

1. Uniform distribution of additives was obtained by separately adding dispersed Al paste, silica microparticles (AS) or milled carbon fibre (AP) into prepared forming mixture of autoclaved aerated concrete (AAC), and by stirring all mass for 1 min. Optimal amount of additives was determined as follows: AS – 1.0%, AP – 0.1% sand mass.
2. High pozzolanic activity having AS and binding material in question an inert AP additives marginally changes AAC forming mixtures spreadability, height of expansion and maximum temperature, however significantly increases plasticity strength: AS additive up to 286%, AP – 153%.

3. AS additive has an influence on AAC properties:
 - changes AAC macrostructure by formation of more spherical shape, smaller and more evenly distributed closed pores;
 - during the autoclave curing, additive particles more intensively react with lime than with milled sand resulting in a well-formed efflorescent lamellar tobermorite;
 - due to mentioned reasons AAC compressive strength increases up to 20%, and flexural strength up to 31%.
4. It is found that the fine milled carbon fibre (with activated surface) additive also has a positive effect on AAC properties:
 - during the hydrothermal treatment of AAC, very fine particles act as crystallization centers and overgrow pin-shaped calcium hydrosilicates, and this ensures a good contact with the walls of inter-pores;
 - due to mentioned reasons, AAC compressive strength increases up to 20%, and flexural – up to 8%.
5. More micropores form in the wall microstructure of fine micropores. Increased closed porosity thermal conductivity reduces up to 12% and water vapour permeability – up to 7% of AAC produced with 1.0% AS additive, while AAC with 0.1% AP: up to 9% and 3%.
6. Thermal shrinkage of AAC decreases due to high crystallinity of calcium hydrosilicates and enhanced carcass. Such AAC can be used as heat resistant material with sanding up to 700 °C.
7. Compressive and flexural strength results of AAC made with AS and AP additives are summarized statistically. Proposed regression equations allow to predict AAC compressive and flexural strength values when the density is in the range of 400–450 kg/m³.

List of published works on the topic of the dissertation In the reviewed scientific periodical publications

Laukaitis, A.; Kerienė, J.; Kligys, M.; Mikulskis, D.; Lekūnaitė, L. 2010. Influence of amorphous nanodispersive SiO₂ additive on structure formation and properties of autoclaved aerated concrete, *Materials science (Medžiagotyra)* 16(3): 257–263, ISSN 1392-1320. (Thomson ISI Web of Science).

Laukaitis, A.; Kerienė, J.; Kligys, M.; Mikulskis, D.; Lekūnaitė, L. 2012. Influence of mechanically treated carbon fibre additives on structure formation

and properties of autoclaved aerated concrete, *Construction and building materials* 26(1): 362–371, ISSN 0950-0618. (Thomson ISI Web of Science).

Lekūnaitė, L.; Laukaitis, A.; Kligys, M.; Mikulskis, D. 2012. Investigations into parameters of forming mixtures of autoclaved aerated concrete with nanoadditives, *Materials science (Medžiagotyra)* 18(3): 284–289, ISSN 1392-1320. (Thomson ISI Web of Science).

In the other editions

Balčiūnas, G.; Lekūnaitė, L.; Laukaitis, A. 2011. SiO₂ mikrodulkių poveikis dujų cementbetonio, su mišria rišamąja medžiaga, stipruminėms savybėms, *14-osios Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis“ 2011 metų teminės konferencijos „Statyba“ (2011 m. kovo 23–25 d.) straipsnių rinkinys*: 1–4, ISBN 978955289296.

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Lina Lekūnaitė was born on 18 of December, 1984 in Biržai. In 2007 she was granted the Bachelor's Degree on Building Materials and Products at Vilnius Gediminas Technical University, Faculty of Building Engineering. In 2009 she was granted the Master's Degree on Building Materials and Products at Vilnius Gediminas Technical University, Faculty of Building Engineering. In 2009–2013 PhD student at Vilnius Gediminas Technical University. Presently she works as a junior research scientist in Vilnius Gediminas Technical University Scientific Institute of Thermal Insulation.

KALCIO HIDROSILIKATŲ SUSIDARYMĄ INTENSYVINANČIŲ PRIEDŲ POVEIKIS AUTOKLAVINIO AKYTOJO BETONO FORMAVIMO MIŠINIŲ IR PRODUKTŲ SAVYBĖMS

Problemos formulavimas. Pagal Statybos produktų reglamento 305/2011, kuris pakeičia statybos produktų direktyvą 89/106/EEC, vienas iš septynių esminių statinių reikalavimų yra energijos taupymas ir išsaugojimas. Pagal šį reikalavimą statiniams šildyti turi būti suvartojama kuo mažiau energijos.

Nuolat griežtėjant pastatų atitvarų šiluminės varžos reikalavimams, akylasis betonas vis plačiau naudojamas mažaaukštėje statyboje, todėl vis dažniau juo keičiamos tradicinės keramikos arba silikatinės plytos.

Pagrindinė autoklavinio akytojo betono (AAB) gaminių naudojimo sritis yra pastatų atitvaros. AAB turi daug teigiamų savybių. Šio betono gamybai

naudojamos plačiai paplitusios natūralios žaliavos: kalkės, kvarcinis smėlis, portlandcementis ir vanduo. Todėl šią medžiagą galima vadinti ekologiška. Yra gana nesudėtinga dirbti su AAB gaminiais, nes jis yra lengvas ir paprastai apdorojamas (pjauštomas, frezuojamas, gręžiamas), yra nedegus ir atsparus puvimo procesams.

AAB pasižymi pakankamai geromis konstrukcinėmis, termoizoliacinėmis ir akustinėmis savybėmis. Priklausomai nuo tankio ($400\text{--}600\text{ kg/m}^3$) šilumos laidumo koeficientas gali kisti nuo $0,080\text{ W/(m}\cdot\text{K)}$ iki $0,16\text{ W/(m}\cdot\text{K)}$. Šiuo metu AAB naudojamas mažaukščių gyvenamųjų namų statyboje kaip konstrukcinė ir termoizoliacinė medžiaga. AAB blokais galima užpildyti daugiaaukščių karkasinių pastatų angas.

Pagrindinė akytųjų betonų stiprumo savybė – gniuždymo stipris, tačiau jis yra nedidelis. Gniuždymo ir lenkimo stiprius galima padidinti naudojant kalcio hidrosilikatų susidarymą intensyvinančius pucolaninius arba pluoštinius priedus. Šiame darbe kaip pucolaninis priedas buvo naudotos SiO_2 mikrodulkės, o kaip pluoštinis – maltas anglies pluoštas.

Panaudojus AAB gamybai anglies pluošto ir SiO_2 mikrodulkių priedus, galima išplėsti jo naudojimo sritį, t. y. AAB panaudoti kaip kaitrai atsparią medžiagą (iki $700\text{ }^\circ\text{C}$).

Darbo aktualumas. Sandėliavimo ir vežimo metu hermetiškai supakuoti AAB gaminiai dėl susikaupusios drėgmės praranda iki 30 % stiprio, tad aktualu naudoti priedus, kurie pagerintų AAB gaminių stiprumo savybes. Sustiprinus akytąjį betoną būtų galima jį palengvinti ir pagaminti stiprią termoizoliacinę medžiagą. Vieni iš tokių priedų yra SiO_2 mikrodulkės ir maltas anglies pluoštas. Norint gauti minėtas savybes, reikia nustatyti geriausius SiO_2 mikrodulkių ir malto anglies pluošto priedų kiekius bei išspręsti šių priedų ir Al pastos tolygų pasiskirstymą.

AAB su SiO_2 mikrodulkių priedu kompleksškai ištirtas nebuvo. Todėl šiame darbe nagrinėjamas jo poveikis AAB formavimo mišinių savybėms: konsistencijai, išsipūtimui, didžiausiajai temperatūrai (rišamųjų medžiagų hidratacijai), plastiškajam stipriui ir betono savybėms: mikro- ir makrostruktūrai, šilumos laidumui, laidumui vandens garams ir atsparumui šalčiui. Analogiškai buvo tirtas rutuliniu malūnu malto anglies pluošto priedo poveikis.

Tyrimų objektas – autoklavinis akytasis betonas su kalcio hidrosilikatų susidarymą intensyvinančiais silicio dioksido mikrodulkių ir malto anglies pluošto priedais.

Darbo tikslas. Kompleksiškai ištirti silicio dioksido mikrodulkių ir malto anglies pluošto priedų poveikį autoklavinio akytojo betono formavimo mišiniui ir bandinių savybėms.

Darbo uždaviniai. Darbo tikslui pasiekti disertacijoje reikia spręsti šiuos uždavinius:

1. Nustatyti geriausius SiO_2 mikrodulkių ir malto anglies pluošto priedų kiekius.
2. Ištirti SiO_2 mikrodulkių ir malto anglies pluošto priedų poveikį autoklavinio akytojo betono formavimo mišinių konsistencijai, didžiausiajai temperatūrai, išsipūtimo aukščiui, plastiškajam stipriui.
3. Nustatyti minėtų priedų poveikį autoklavinio akytojo betono savybėms (tankiui, makro- ir mikrostruktūrai, fazinei kalcio hidrosilikatų sudėčiai, gniuždymo ir lenkimo stipriams, terminėi susitraukčiai, šilumos laidumui, laidumui vandens garams, atsparumui šalčiui).
4. Parengti modifikuoto autoklavinio akytojo betono su priedais technologinę gamybos schemą.

Tyrimų metodai. Šiame darbe AAB formavimo mišinių savybės buvo nustatytos remiantis Martinenko ir Morozov apibendrinta metodu. AAB stiprumo savybės buvo nustatytos pagal LST EN 679 ir LST EN 1351 standartų reikalavimus. Tankis nustatytas remiantis LST EN 678 standartu. Makrostruktūra nustatyta optiniu mikroskopu „Motic“, struktūros nuotraukų analizei panaudotos „UTHSCSA Image tool“ ir „Pixcavator Image Analysis“ programos. Medžiagų mikrostruktūrai tirti ir analizuoti naudotas skenuojantis elektroninis mikroskopas „JSM 6490 LV“ ir porozimetras „PoroMaster 33“. Rentgenografiniai tyrimai atlikti rentgeno difraktometru „DRON-7“, termografiniai tyrimai – derivatografu „Linseis STA PT-1600“, o terminė susitrauktis – dilatometru „LINSEIS L76“. Stiprumo savybių tyrimų rezultatams apdoroti taikyti matematiniai statistiniai metodai. AAB šilumos laidumo koeficientui, laidumui vandens garams ir atsparumui šalčiui nustatyti taikyti metodai, pateikti Lietuvos standartuose LST EN 1745, LST EN 772-15 ir LST EN 15304.

Mokslinis naujumas. Darbo mokslinį naujumą rodo gauti šie 6 medžiagų inžinerijos mokslui nauji rezultatai:

1. Darbe kompleksiškai ištirtas AAB su kalcio hidrosilikatų susidarymą intensyvinančiais SiO_2 mikrodulkių ir malto anglies pluošto priedais. Parinkti geriausi minėtų priedų kiekiai ir formavimo mišinių sudėtys. Tolygus priedų pasiskirstymas formavimo mišinyje pasiektas išsklaidant

priedų (su dalimi vandens ir paviršių aktyvinančia medžiaga) ir Al pastos daleles bei parenkant atitinkamą maišymo režimą.

2. Nustatytas priedų poveikis AAB formavimo mišinių savybėms: sklidumui, didžiausiai temperatūrai, išsipūtimo aukščiui, plastiškajam stipriui.

3. Nustatyta, kad SiO_2 mikrodulkių ir malto anglies pluošto priedai sustiprina AAB porų sienelės. SiO_2 mikrodulkių priedas, jau būdamas pradinėje stadijoje, skatina C-S-H susidarymą, terminio apdorojimo metu sudarydamas gerą sąlyčio zoną su nesureagavusia smėlio dalele. Malto anglies pluošto dalelių paviršius veikia kaip kalcio hidrosilikatų kristalizacijos centrai. Todėl modifikuotas AAB turi geresnes stiprumo savybes ir mažesnę terminę susitrauktį.

4. Naudojant priedus AAB struktūroje susidaro daugiau uždarytų porų, todėl sumažėja sukiestėjusio betono šilumos laidumas ir laidumas vandens garams.

5. Statistiškai apdorojus bandymų rezultatus išvestos regresinės lygtys, kuriomis remiantis galima prognozuoti $400\text{--}450 \text{ kg/m}^3$ tankio intervale taškinės AAB gniuždymo ir lenkimo stiprių vertes.

6. Panaudojus minėtus priedus gautas $\sim 450 \text{ kg/m}^3$ tankio AAB, kurio gniuždymo stipris $\sim 4 \text{ MPa}$, lenkimo stipris $\sim 2 \text{ MPa}$, šilumos laidumo koeficientas $\sim 0,1 \text{ W/(m}\cdot\text{K)}$, terminė susitrauktis $\sim 1 \%$.

Darbo rezultatų praktinė reikšmė. AAB pagamintas su $1,0 \%$ SiO_2 mikrodulkių arba $0,1 \%$ malto anglies pluošto priedu savo fizikinėmis ir mechaninėmis bei šiluminėmis ir techninėmis savybėmis yra pranašesnis už AAB be priedų. Didesnis formavimo masės plastiškasis stipris leidžia sutrumpinti technologinių operacijų trukmę. AAB, pagamintas su SiO_2 mikrodulkių ir malto anglies pluošto priedu, pasižymi mažesne terminė susitrauktimi. Tai užtikrina jo naudojimą temperatūroje iki 700°C kaip kaitrai atsparų betoną.

Ginamieji teiginiai

1. SiO_2 mikrodulkių ir malto anglies pluošto priedai turi poveikį autoklavinio akytojo betono formavimo mišinių konsistencijai, didžiausiai temperatūrai, išsipūtimo aukščiui, plastiškajam stipriui, makro- ir mikrostruktūroms.

2. SiO_2 mikrodulkių priedas intensyvina hidrosilikatinę kietėjimą, o malto anglies pluošto priedai autoklavinio kietinimo metu veikia kaip kristalizacijos centrai, skatina kalcio hidrosilikatų susidarymą ir kristalizaciją. Tokio modifikuoto autoklavinio akytojo betono stiprumo savybės geresnės.

Disertacijos struktūra. Darbo apimtis 83 puslapiai (be priedų), tekste panaudota 13 numeruotų formulių, 46 paveikslai ir 5 lentelės. Rašant disertaciją buvo naudotos 129 literatūros šaltiniai.

Disertaciją sudaro įvadas, trys skyriai, bendrosios išvados, naudotos literatūros ir autoriaus publikacijų disertacijos tema sąrašai.

Įvadiniamе skyriuje aptariama tiriamoji problema, darbo aktualumas, aprašomas tyrimų objektas, formuluojamas darbo tikslas bei uždaviniai, aprašomi tyrimų metodai, darbo mokslinis naujumas, darbo rezultatų praktinė reikšmė, ginamieji teiginiai.

Pirmajame skyriuje pateikta AAB su priedais apžvalga. Skyriaus pabaigoje pateiktos literatūrinės apžvalgos išvados ir disertacijos uždaviniai.

Antrajame skyriuje aprašytos AAB su priedais tyrimams naudotos medžiagos, pateiktos pagrindinės jų charakteristikos. Taip pat aprašyti taikyti tyrimų metodai ir naudota įranga.

Trečiajame skyriuje pateikti kalcio hidrosilikatų susidarymą intensyvinančių AS bei AP priedų ir jų kiekio poveikis AAB formavimo mišinių savybėms. Nustatyta, kaip priedai veikia AAB formavimo mišinių sklidumą, temperatūrą, išsipūtimo aukštį bei plastiškąjį stiprį. Taip pat šiame skyriuje tirta, kaip minėti priedai keičia sukietėjusio AAB tankį, ultragarso impulso greitį, terminę susitrauktį, šilumos laidumą, laidumą vandens garams, atsparumą šalčiui, gniuždymo bei lenkimo stiprius, pateikta AAB su priedais makro- bei mikrostruktūrų analizė. Gauti stipruminių savybių rezultatai apdoroti statistiškai. Remiantis atliktų tyrimų rezultatais parengta AAB su AS ir AP priedais gamybos technologinė schema.

Darbo pabaigoje suformuluotos bendrosios išvados.

Bendrosios išvados

1. Tolygus priedų išsklaidymas pasiektas į paruoštą autoklavinio aktyvo betono (AAB) formavimo mišinį pridėjus atskirai išsklaidytų Al pastos, silicio dioksido mikrodulkių (AS) arba malto anglies pluošto (AP) dalelių ir išmaišius 1 min. Nustatyti geriausi priedų kiekiai: AS – 1,0 %, AP – 0,1 % smėlio masės.
2. Dideliu pucolaniniu aktyvumu pasižymintis AS ir rišamosios medžiagos atžvilgiu inertiškas AP priedai nedaug keičia AAB formavimo mišinių sklidumą, išsipūtimo aukštį ir didžiausiąją temperatūrą, tačiau labai padidina plastiškąjį stiprį: AS priedas iki 286 %, AP – 153 %.
3. AS priedas daro poveikį AAB savybėms:
 - keičia AAB makrostruktūrą, susidaro daugiau sferinės formos smulkesnių ir tolygiau pasiskirsčiusių uždarų porų;

- autoklavinio kietinimo metu priedo dalelės intensyviau reaguoja su kalkėmis nei maltas smėlis, dėl to susidaro gerai išsikristalinęs plokštelinės formos tobermoritas;
- dėl išvardytų priežasčių AAB gniuždymo stipris padidėja iki 20 %, o lenkimo – iki 31 %.
- 4. Nustatyta, kad smulkiai maltas anglies pluošto (suaktyvintu paviršiumi) priedas turi teigiamą poveikį AAB savybėms:
- hidroterminio AAB apdorojimo metu labai smulkios priedo dalelės atlieka kristalizacijos centrų vaidmenį, apauga adatėlių formos kalcio hidrosilikatais, tai užtikrina jų gerą sąlytį su porų sienelėmis;
- dėl šių priežasčių AAB gniuždymo stipris padidėja iki 20 %, o lenkimo – iki 8 %.
- 5. AAB su priedais porų senelėse susidaro daugiau smulkių mikroporų. Padidėjus uždaram poringumui sumažėjo AAB pagamintas su 1,0 % AS priedu šilumos laidumo koeficientas iki 12 % ir laidumas vandens garams – iki 7 %, o su 0,1 % AP priedu sumažėja atitinkamai: iki 9 % ir 3 %.
- 6. Dėl didesnio kalcio hidrosilikatų kristališkumo ir tvirtesnio karkaso mažėja AAB terminė susitrauktis. Tokį AAB galima naudoti kaip kaitrai atsparią medžiagą iki 700 °C.
- 7. AAB, pagamintų su AS ir AP priedais, gniuždymo ir lenkimo stiprių rezultatai apibendrinti statistiškai. Išvestos regresinės lygtys, pagal kurias 400–450 kg/m³ tankio intervale galima prognozuoti AAB gniuždymo arba lenkimo stiprio vertes.

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INFLUENCE OF ADDITIVES INTENSIFYING FORMATION OF THE CALCIUM
HIDROSILICATES ON PROPERTIES OF THE FORMING MIXTURES AND
PRODUCTS OF AUTOCLAVED AERATED CONCRETE

Summary of Doctoral Dissertation
Technological Sciences, Materials Engineering (08T)

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