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Rational technology for the use of glass cullet and fly ash in silicate bricks to improve the thermal insulation properties of enclosing structures

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Abstract. A topical issue in the modernization of housing and communal services is increasing the energy efficiency of enclosing structures while maintaining the standard strength and durability of wall materials. The study aimed to investigate opportunities for the use of glass cullet and fly ash in the production of autoclaved silicate bricks to reduce their thermal conductivity. The tested characteristics included average density, the thermal conductivity coefficient, compressive and flexural strength, water absorption, and frost resistance. The introduction of glass powder and fly ash was found to consistently lower the average density of silicate bricks from 1,910–1,950 to 1,625–1,700 kg/m³ and the thermal conductivity from 0.88–0.91 to 0.52–0.54 W/(m•K). The optimal compositions (samples No. 2 and No. 3) reduced thermal conductivity by 25–30% compared to the control sample with compressive strength remaining above 17.5 MPa and frost resistance in the range of F27–F35. An analysis of microstructural and phase characteristics based on SEM and XRD data showed that the improvement of thermophysical properties was due to the formation of a finely porous structure and a mixed hydrate matrix containing tobermorite and an amorphous C–S–H phase. The results confirm the expedience of using glass cullet and fly ash to produce energy-efficient silicate bricks suitable for use in enclosing structures in the framework of modernizing the facilities of housing and community services, which will not require major changes to current production technologies.

Keywords: silicate bricks, glass cullet, glass powder, fly ash, autoclave curing, energy efficiency, enclosing structures, housing and communal services

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1. INTRODUCTION

1.1. Problem Statement

One of the priorities of the construction industry in the modernization and renovation of housing and communal services (HCS) is to raise the energy efficiency of enclosing structures while reducing the material consumption and the environmental load of building materials. In countries with a sharply continental climate, which includes the Republic of Kazakhstan, loss of heat through exterior walls remains one of the leading factors in the growth of operating costs and greenhouse gas emissions. This is the reason for increased interest in the development of energy-efficient wall materials with reduced thermal conductivity and sufficient operational reliability.

Silicate bricks are traditionally widely used in civil and industrial construction due to their high geometric accuracy, strength, fire resistance, and stable properties. However, the main drawback of this material is its relatively high average density and, as a result, higher thermal conductivity, which limits the application of silicate bricks in energy-efficient enclosing structures without additional insulation. In the framework of housing stock modernization, where increased wall thickness or complex multilayer systems are not always technologically and economically feasible, the task of purposefully lowering the thermal conductivity of the wall material itself while maintaining standard strength and durability indicators becomes urgent.

One promising solution to this problem is the rational use of technogenic and secondary mineral resources, in particular glass cullet and fly ash from thermal power plants. Glass cullet, generated in great volumes from household and industrial waste, is marked by a high content of amorphous silicon dioxide, chemical inertness, and potential pozzolanic activity when finely ground. Fly ash, in turn, is a fine aluminosilicate material capable of participating in the formation of a porous structure and modifying the phase composition of autoclaved silicate materials.

Recent studies show that the introduction of microdisperse silica-containing additives into the composition of silicate products allows changing hydrothermal hardening processes, achieving a more developed pore structure, and lowering the thermal conductivity coefficient. However, the issue of the optimal ratio of glass powder and fly ash to balance the thermophysical and strength characteristics of silicate bricks remains understudied. Several studies note that an excessive decrease in density can compromise the frost resistance and bearing capacity of products, which is especially critical for operation under cyclic freezing and thawing.

In the context of environmental management programs and the transition to circular economy principles, the use of glass cullet and fly ash in the production of silicate bricks has a double effect. On the one hand, it makes use of waste and thus reduces the load on landfills. On the other hand, the resulting energy-efficient building materials help reduce heat loss in buildings and lower operating costs in the HCS sector. These benefits fully correspond to the priority areas of program-targeted financing of the Republic of Kazakhstan focused on the greening of the construction industry and the modernization of the housing stock.

In connection with the above, there is an urgent scientific and practical task to develop rational technology for the production of silicate bricks using glass cullet and fly ash that would provide lower thermal conductivity while maintaining the standard indicators of strength, water absorption, and frost resistance. Of particular interest is the experimental study of the effect of varying degrees of substitution of the traditional silicate mass with glass powder and fly ash on the physical and mechanical properties of the material, as well as the determination of optimal compositions for enclosing structures as part of the modernization of HCS facilities.

The present study aims to comprehensively assess the impact of glass cullet and fly ash on the density, thermal conductivity, strength, and performance characteristics of silicate bricks and to substantiate rational compositions that increase the thermal insulation properties of enclosing structures without compromising their durability.

1.2. Energy Efficiency of Enclosing Structures and the Role of Silicate Bricks

Improving the energy efficiency of enclosing structures is one of the key tasks of modern construction, especially in the context of HCS modernization. A significant share of heat losses in buildings owes to the high thermal conductivity of traditional wall materials, including silicate bricks [1, 2]. Despite their high strength, geometric accuracy, and durability, classic silicate bricks have higher average density, which elevates the thermal conductivity coefficient and reduces the energy efficiency of buildings [1, 3, 4].

Therefore, research is actively investigating ways to modify silicate products to reduce their density and thermal conductivity without losing strength and performance characteristics [2-4].

1.3. Autoclaved Silicate Materials: Phase Formation and Microstructure

The properties of silicate bricks are determined by hydrothermal reactions in the $CaO–SiO_2–H_2O$ system under autoclave conditions. The main products of curing are low-base calcium hydrosilicates (C–S–H) and crystalline tobermorite, the ratio of which defines the strength, water absorption, and frost resistance of the material [5-8].

Studies have shown that the crystallinity and morphology of tobermorite significantly depend on the composition of the original silica, the Ca/Si ratio, and the presence of impurity ions [5, 8-10]. In this case, amorphous or fine silica can accelerate reactions and change the kinetics of phase formation in contrast to inert quartz [6, 7].

1.4. Glass Cullet as an Alternative Silica-Containing Component

Glass cullet is a type of technogenic waste generated in massive amounts. Consisting mainly of amorphous silicon dioxide, glass cullet is a promising substitute for quartz sand in silicate products [11-14]. Several studies have shown that a partial or complete replacement of quartz sand with recycled glass changes in the density, strength, and microstructure of silicate materials [12, 13].

Borek and colleagues demonstrated the possibility of obtaining silicate products with increased strength and reduced density using glass and glass powder of various dispersions [11, 12]. Similar results were obtained using glass sand in stable autoclaved materials, which confirms the reactivity of glass under hydrothermal conditions [13, 14].

1.5. Effect of Alkaline Glass Components on Phase Composition

Unlike quartz, glass contains a significant amount of alkaline oxides (Na_2O, K_2O), which can influence phase formation in autoclaved silicate systems [6, 9, 15]. It has been experimentally proven that Na^+ ions can inhibit the crystallization of tobermorite, promoting the formation of a less crystalline C–S–H phase [6, 9, 10].

Studies of the hydrothermal synthesis of tobermorite from glass precursors confirm that the chemical composition of glass and the concentration of alkalis have a decisive effect on the morphology and crystallinity of the formed phases [8-10, 15].

1.6. Glass Waste in Autoclaved Aerated Concrete as a Related System

Autoclaved aerated concrete (AAC) is considered a related system in hardening chemistry. Studies have shown that the introduction of glass powder into AAC changes the structure of tobermorite and C–S–H and affects the density, strength, and thermal conductivity of the material [16-18].

The works of Walczak et al. and more recent studies on the use of municipal glass cullet in AAC confirm that glass can be effectively utilized in autoclaving technologies, subject to optimal dosages and curing regimes [16-18].

1.7. Fly Ash in Autoclaved Silicate and Lime-Sand Systems

Fly ash from thermal power plants is widely studied as a component of lime-sand-based autoclaved bricks. It has been shown that the introduction of fly ash helps lower the average density and thermal conductivity of products due to the formation of a more developed porous structure [19, 20].

Classical studies by Cicek & Tanrıverdi [20] and Kumar [19] confirmed the possibility of obtaining autoclaved bricks with satisfactory strength and thermophysical characteristics with a rational "lime–sand–ash" composition.

1.8. Reduction of Thermal Conductivity Using Secondary Glass Products

A separate area of research deals with the use of granular foam glass and glass-ceramic materials in silicate products. Such additives have been found to significantly reduce thermal conductivity due to an increased proportion of closed pores [3, 4, 21].

Experimental data confirm that the reduction of thermal conductivity should be accompanied by the control of strength and water absorption, especially for the operating conditions of enclosing structures in a climate with freeze-thaw cycles [1, 3, 4, 21].

1.9. Water Absorption, Durability, and Performance Aspects

Water absorption and the humidity state of brickwork strongly impact the actual thermal conductivity of the walls [1]. Studies show that even at the same density, an increase in operating humidity leads to an increase in λ, which must be considered when assessing the energy efficiency of silicate bricks [1, 2].

1.10. Relationship with Alkali-Silica Reaction Studies

Although silicate bricks are not a type of cement composite, studies on the alkali-silica reaction (ASR) in systems using glass cullet are methodologically important. It has been shown that fine glass can exhibit pozzolanic activity and reduce the risk of harmful expansions, while large glass fractions are more susceptible to the ASR [22-28].

These findings are important for substantiating the choice of the fractional composition of glass powder and alkalinity control in the development of autoclaved silicate products [22-28, 29-33].

1.11. Glass Cullet in Fired Bricks and Sustainable Construction

There is a significant body of publications devoted to the use of glass waste in fired clay bricks. In particular, glass has been shown to improve the physical and mechanical properties of bricks and lower their thermal conductivity due to the fluxing effect and changes in porosity [34-37].

Research confirms the general trend in the incorporation of glass waste in the production of building materials and stresses the environmental and economic feasibility of such solutions [30, 34-38].

Our literature review [1-40] suggests that glass cullet and fly ash are promising components of autoclaved silicate materials that can simultaneously address the problems of waste disposal, reducing density, and increasing thermal insulation properties. However, information on the rational combinations of glass powder and fly ash specifically for silicate bricks suitable for the modernization of the enclosing structures of HCS objects is insufficiently systematized, which defines the relevance of this study.

2. METHODS AND MATERIALS

2.1. Raw Materials

The basic raw material in the composition of autoclaved silicate bricks was the traditional silicate mass used in industrial production by "West Kazakhstan Corporation of Building Materials" JSC (ZKKSM, JSC).

The silica component for the tested bricks was quartz-feldspar sand from the "Melovyye Gorki" deposit located 5.5–6 km southeast of Uralsk, Kazakhstan. The chemical composition of the sand is given in Table 1, and its physical and mechanical characteristics are listed in Table 2.

Table 1. Chemical analysis of sand.

Sand deposit	Oxide content, %								
	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	R_2O	SO_3	LOI	∑
Melovyye Gorki	83.5	2.5	2.9	4.3	1.3	1.6	2.7	1.2	100

Note: LOI – loss on ignition.

Table 2. Physical and mechanical properties of sand.

Sand deposit	Characteristic				
	fineness modulus	bulk density, kg/m^3	true density, g/cm^3	void ratio, %	contamination, %
Melovyye Gorki	1.49	1485	2.63	44	0.9

The chosen sand is characterized by a high content of SiO_2 (83.5%), which meets the requirements for raw materials for the production of silicate bricks.

The physical and mechanical properties of the sand (fineness modulus, true density, and the content of contaminants) make it suitable for silicate systems and provide for a homogeneous structure of molded products.

Slaked lime used as a binder has a high reactivity in the $CaO–SiO_2–H_2O$ system, which is a key factor for the synthesis of hydrosilicate phases under autoclave curing conditions.

2.2. Modifying Additives

The modifying components tested in the study were glass powder and fly ash.

Glass powder of the indicated fraction was chosen for its increased reactivity in the $CaO–SiO_2–H_2O$ system and ability to actively participate in hydrothermal reactions during autoclaving. Fly ash was examined as a component contributing to the formation of a more developed porous structure and lowering the average density of silicate products.

Glass powder was obtained by mechanically grinding container glass waste generated by "Stekloservis," JSC (Fig. 1) (Uralsk, Kazakhstan). Glass cullet was supplied both in metal containers and in large-capacity soft bags (big bags, FIBCs – Flexible Intermediate Bulk Containers), as is customary in the industrial practice of handling secondary glass waste.

a) b)

Fig. 1. General view of glass cullet generated by "Stekloservis," JSC: a – collected in metal containers, b – collected in big bags.

The amorphous structure of glass powder and its high dispersity make it possible to increase the reactivity of this component under the hydrothermal conditions of autoclave curing and to intensify the formation of calcium hydrosilicates.

Fly ash from Ekibastuz GRES-2

The aluminosilicate component used in the study was fly ash from Ekibastuz GRES-2. The granulometric composition of the material given in Table 3 indicates its polydisperse nature and ability to effectively fill the intergranular space in the silicate mass.

Table 3. Results of particle size analysis of fly ash from "Ekibastuz-GRES-2".

No.	Name	Dv(10), µm	Dv(50), µm	Dv(90), µm
1	Fly ash from "Ekibastuz-GRES-2"	7.83	70.4	218

The microstructure of fly ash at different magnifications and its EDS spectrum are shown in Fig. 2. The ash was found to be characterized by a combination of spherical glassy particles and porous aggregates of irregular shapes, which is typical of the ashes produced by high-temperature coal combustion.

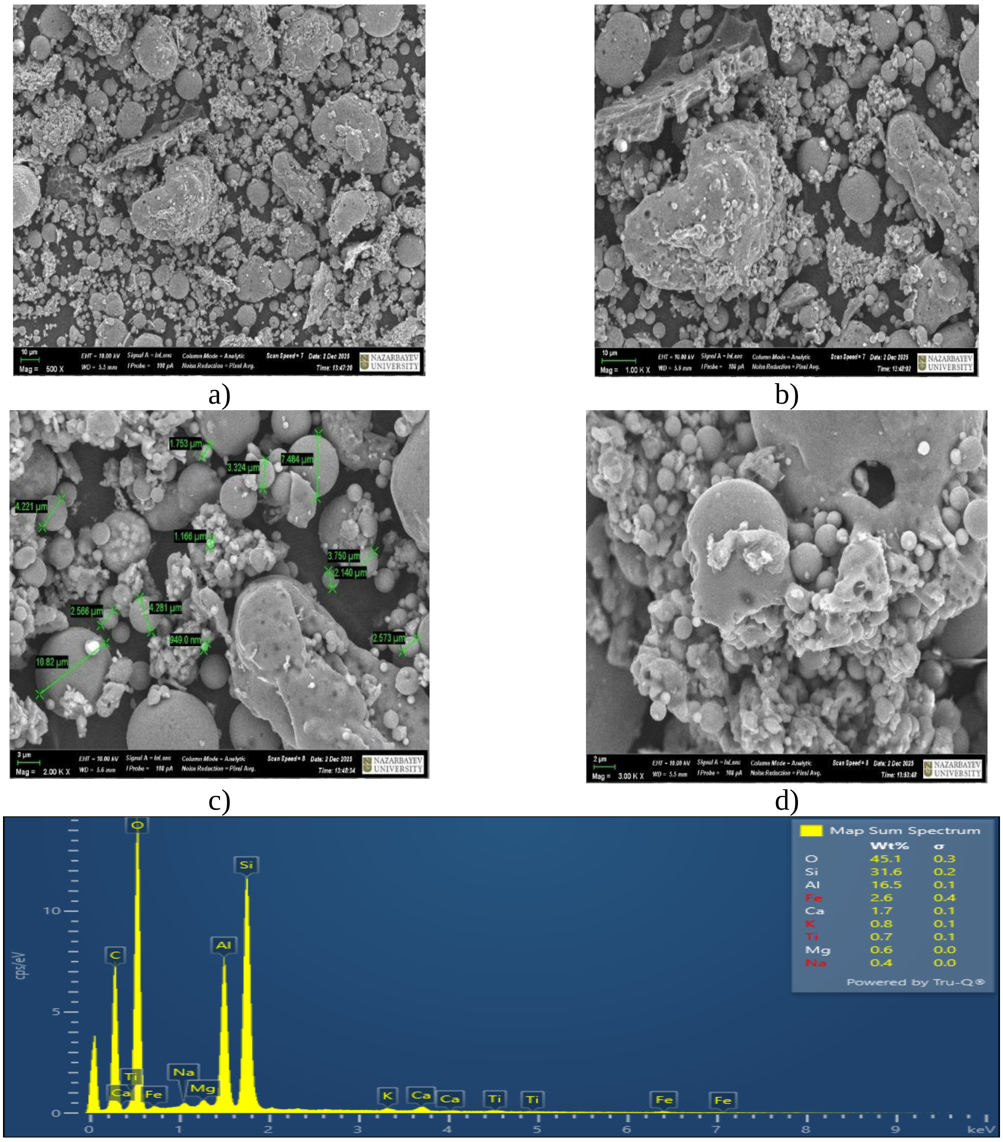

Fig. 2. SEM micrographs of fly ash from Ekibastuz GRES-2 at different magnifications: (a–d) – polydisperse microstructure of the material, characterized by a predominance of spherical glassy particles (microspheres) and porous aggregates of irregular shape; e) – EDS spectrum showing the elemental composition of fly ash.

The particle morphology of fly ash and the presence of a developed amorphous aluminosilicate phase suggest its high reactivity under hydrothermal conditions, as well as its ability to participate in the formation of a hydrosilicate matrix in autoclaved silicate materials.

The observed spherical particles have a relatively smooth surface and are glassy, which points to the amorphous aluminosilicate nature of the ash. There are larger porous fragments of irregular shape, which are partially melted aggregates enriched with silicon and aluminum oxides. This morphology is responsible for the high reactivity of fly ash under hydrothermal conditions due to its high specific surface area and the presence of defective zones.

Of particular interest are the fine particles less than 1-2 µm in size, evenly distributed between large spheroids. These particles can effectively fill the intergranular space in the silicate mass, acting as a micro-filler, which contributes to the formation of a denser but finely porous structure of the autoclaved material.

The phase (mineralogical) composition of fly ash was determined by X-ray phase analysis. The results of identification of crystalline and amorphous phases for different samples of fly ash from Ekibastuz GRES-2 are given in Table 4.

Table 4. Mineral (phase) composition of fly ash samples from GRES-2.

No.	Sample No.	Crystal phase	Chemical formula
1	1(XRD)	Amorphous peak	
2	2(XRD)	Amorphous peak	
3	3(XRD)	Sodalite; Aluminum Silicon Oxide; Mullite, syn Trabzonite	$Na_8 (Al_6Si_6O_{24}) (OH)_2 (H_2O)_2$; $Al_2(Al_{2.556} Si_{1.444}) O_{9.722}$; $Ca_4((SiO_3)_3(O H))(OH)$
4	4(XRD)	Magnesioferrite; Quartz alpha; nonacalcium cyclo-hexaaluminate	$(MgFe_2)O_4$; SiO_2 $Ca_9 (Al_2O_6)_3$

Several samples are dominated by an amorphous component, which manifests itself as a diffuse amorphous peak. This suggests a glass-like nature of a significant part of the material.

Along with the amorphous phase, some samples contain crystalline phases such as sodalite, mullite, quartz (α-SiO_2), magnesioferrite, and calcium aluminosilicates (including trabzonite and nonacalcium cyclohexaaluminate), the chemical formulae of which are provided in Table 4. The presence of mullite confirms the aluminosilicate nature of fly ash and its potential ability to participate in the formation of C–(A)–S–H phases under autoclave curing conditions, while quartz and magnesioferrite are relatively inert phases.

The spectra demonstrate the predominance of oxygen, silicon, and aluminum, consistent with the phase composition given in Table 4, as well as the presence of Ca, Fe, Mg, Na, and K in smaller quantities. The combination of the amorphous aluminosilicate phase and the listed crystalline components is favorable for hydrothermal reactions and the formation of a hydrosilicate matrix of autoclaved silicate materials.

Such a chemical composition is favorable for autoclave synthesis for several reasons:

- SiO_2 acts as the primary source of silica for the formation of calcium hydrosilicates;
- Al_2O_3 can partially isomorphically replace Si^{4+} in the C–S–H structure, forming C–(A)–S–H phases;
- the presence of CaO and alkaline oxides helps activate ash and accelerate hydrothermal reactions.

2.3. Compositions of Test Samples

A series of samples of silicate bricks with different degrees of substitution of the traditional silicate mass with glass powder and fly ash were prepared for the study. The compositions of the experimental samples are detailed in Table 5.

Table 5. Tested compositions of silicate bricks using glass powder and fly ash.

Sample No.	Silicate mass, wt%	Glass powder (10-20 μm), wt%	Fly ash, wt%
Control	100	0	0
1	85	5	5
2	80	10	10
3	75	10	15
4	70	10	20

Note: The silicate mass included quartz sand and air-slaked lime. The glass powder was obtained from waste container glass and had an average particle size of 10-20 μm. Fly ash was used as a fine aluminosilicate component.

The control composition used was silicate bricks by "ZKKSM," JSC, made of 100% silicate mass without glass powder and fly ash additives.

This approach made it possible to trace the effect of a gradual increase in the proportion of secondary silica-containing components on the physical, mechanical, and thermophysical characteristics of silicate bricks.

2.4. Sample Preparation and Curing Procedure

The silicate mixture was prepared in laboratory conditions using a technology approximated as much as possible to the industrial production of silicate bricks. The starting components (silicate mass, glass powder, and fly ash) were dosed by weight per the compositions given in Table 1, after which they were dry mixed to obtain a homogeneous composition. Next, water was added to the mixture in an amount of 10-12% of the dry weight, providing molding humidity characteristic of the semi-dry pressing of silicate products.

The samples were then molded by semi-dry pressing at a specific pressure of 20 MPa. To determine the compressive strength and thermophysical characteristics, cylindrical samples were made with dimensions of 50 × 50 × 50 mm. The samples for flexural strength tests were molded in the shape of beams measuring 40 × 40 × 160 mm in line with the generally accepted practice of determining the flexural strength of silicate materials.

After molding, the samples were pre-aged under normal conditions to stabilize the structure and then sent for autoclaving.

Autoclave curing was carried out according to the factory production mode for silicate bricks used at "ZKKSM," JSC. The autoclaving mode consisted of the following steps:

- raising the temperature and pressure of saturated water steam to 180–190°C at 0.8–1.2 MPa;
- isothermal exposure at the specified parameters for 6–8 hours;
- controlled decrease of pressure and temperature to atmospheric conditions.

The autoclave cycle lasted a total of 8–10 hours, which corresponds to the industrial conditions for curing silicate bricks. The selected mode enabled the hydrothermal reactions between lime and silica-containing components (quartz sand, glass powder, and fly ash) with the formation of calcium hydrosilicates, which form the structural frame of the material.

The use of the industrial autoclaving ensured the comparability of the obtained experimental data with the real conditions of silicate brick production, increasing the practical significance of the findings for use in construction and in the modernization of HCS.

2.5. Methods

After autoclaving, the samples were subjected to a series of physical, mechanical, and thermophysical tests.

- Average density was calculated from the weight and geometric dimensions of dried samples by the standard method.
- Water absorption was determined by saturating samples with water to constant weight and calculated as the ratio of weight gain to dry sample weight.

- Compressive strength was determined on a hydraulic press, applying load uniformly until destruction.
- Flexural strength was determined by the standard three-point flexure test.
- Frost resistance was evaluated by the cyclic freeze-thaw method, recording the number of cycles withstanded without visible signs of destruction and significant loss of strength.
- The thermal conductivity coefficient was determined under steady-state heat flux conditions and the established temperature.

All tests were performed on at least three parallel samples of each composition, averaging the results. The obtained data were used to compare the effects of glass powder and fly ash on the properties of silicate bricks.

3. RESULTS AND DISCUSSION

3.1. Effect of Composition on Average Density and Thermal Conductivity

The obtained results unambiguously show (Fig. 3) that the partial replacement of the traditional silicate mass with glass powder (10–20 μm) and fly ash leads to a systematic decrease in average density and, as a result, to a significantly lower thermal conductivity coefficient λ. The control composition had the following values: ρ = 1,910–1,950 kg/m³ and λ = 0.88–0.91 W/(m·K).

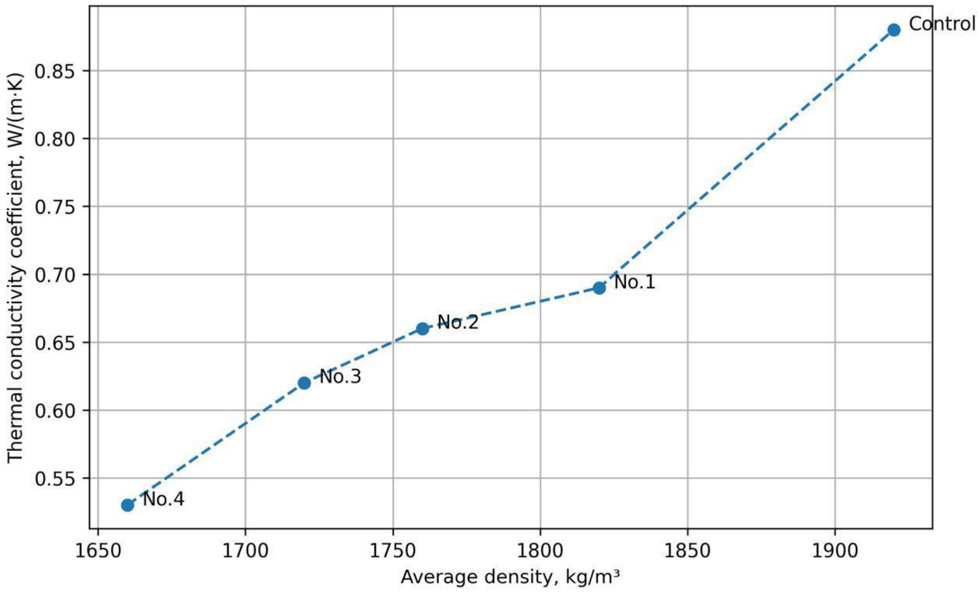

Fig. 3. Dependence of the thermal conductivity coefficient on the average density of silicate bricks with the substitution of silicate mass by glass powder and fly ash.

Already with a moderate modification (sample No. 1: 5% glass powder + 5% fly ash), the average density reduces to 1815–1820 kg/m³ and thermal conductivity lowers to 0.69–0.70 W/(m·K), meaning a more than 20% decrease in λ relative to the control.

This behavior is consistent with a well-known pattern of stone wall materials: λ increases with density and humidity because of the increase in the proportion of the "solid" phase and/or water in the pores, which intensifies heat transfer [1, 11].

A further increase in the proportion of secondary components enhances the effect. The values obtained for sample No. 2 (10% glass powder + 10% fly ash) are ρ = 1760–1775 kg/m³ and λ = 0.65–0.67 W/(m·K); for sample No. 3 (10% glass powder + 15% fly ash) – ρ = 1720–1730 kg/m³ and λ = 0.61–0.64 W/(m·K); and for sample No. 4 (10% glass powder + 20% fly ash) – ρ = 1650–1700 kg/m³ and λ = 0.52–0.54 W/(m·K).

The resulting virtually monotonous "ρ↓ → λ↓" series methodologically agrees with the results of studies on the thermal conductivity of bricks and masonry, where density (along with humidity) acted as a determining factor [1, 11].

The accuracy of our interpretation is confirmed by world studies on autoclave lime-silica materials. In sand-lime materials, the use of secondary silica-containing glass-based components has been shown to reduce density and simultaneously improve/maintain several performance characteristics, which is explained by changes in the microstructure and pore space [5, 6]. In particular, studies on replacing quartz sand with recycled glass show that the obtained lime-silica products can have a lower density relative to control samples under comparable technological conditions [5]. In addition, the result showed sensitivity to the type of glass used (including by composition/color) and the degree of sand substitution [6].

Considering the mechanism of λ reduction, the most likely is an increase in the share of air pores and a change in their size distribution, as well as a possible effect of glass powder and fly ash on hydrothermal phase formation (C–S–H/tobermorite) and the "packing" of particles in the raw material. Studies of hydrothermal lime–quartz systems with added glass powder show that glass (due to their amorphous nature and the presence of alkaline ions) can change the crystallization of tobermorite and increase the proportion of the less crystalline C–S–H phase and reorganize the microstructure and porosity [7]. An important point for our study is that even if the standard strength is maintained, such microstructural reorganization can be fraught with a decrease in density and, as a result, a decrease in thermal conductivity, which is observed experimentally in samples No. 1 – No. 4.

The role of fly ash should be emphasized separately, as this component is often considered a means of forming a "lightweight" structure in lime–silica autoclave systems. Classical studies on fly ash–sand–lime autoclaved bricks demonstrate that the optimization of the composition and mode allows obtaining lightweight products with reduced thermal conductivity, which is logically consistent with the trend of lower ρ and λ with an increase in the share of fly ash in our samples [4]. Furthermore, overviews and applied studies on fly ash-containing bricks/blocks confirm the resource and energy-efficiency potential of fly ash in wall materials, subject to the requirements for strength and water resistance [12].

Finally, the results obtained with sand–lime products modified with foam glass granulate (as a secondary product of glass waste) show a fundamentally similar physical logic: a decrease in λ is achieved due to a higher proportion of porous/air volume and a decrease in material density [3].

Although our study used microdispersed glass powder and not foam glass, both lines of research confirm the general global trend: "glass waste → controlled porosity/density → improved thermal insulation properties of autoclaved wall materials" [3, 5-7].

Thus, we obtain a range of λ = 0.52–0.70 W/(m·K) with a decrease in density to 1,650–1,820 kg/m³ in modified compositions.

This fact is not anomalous but is in good agreement with modern scientific understanding: lower density and the redistribution of the pore space in autoclaved lime-silica materials naturally cause a decrease in the thermal conductivity coefficient [1, 3, 11], while glass cullet/glass powder can act not only as a replacement for the SiO_2-component but also as a factor of microstructural reorganization in hydrothermal conditions [5-7].

3.2. Strength Characteristics and the Substantiation of Optimal Compositions

Despite the pronounced decrease in average density and thermal conductivity, all the studied compositions of silicate bricks demonstrate sufficiently high strength characteristics meeting the requirements for wall materials in load-bearing and self-supporting structures. This combination of properties is fundamentally important for energy-efficient enclosing structures, since decreased thermal conductivity must not be accompanied by a critical deterioration in the bearing capacity of the material [5, 6].

Changes in the physical and mechanical properties of the samples depending on the composition are shown in Fig. 4.

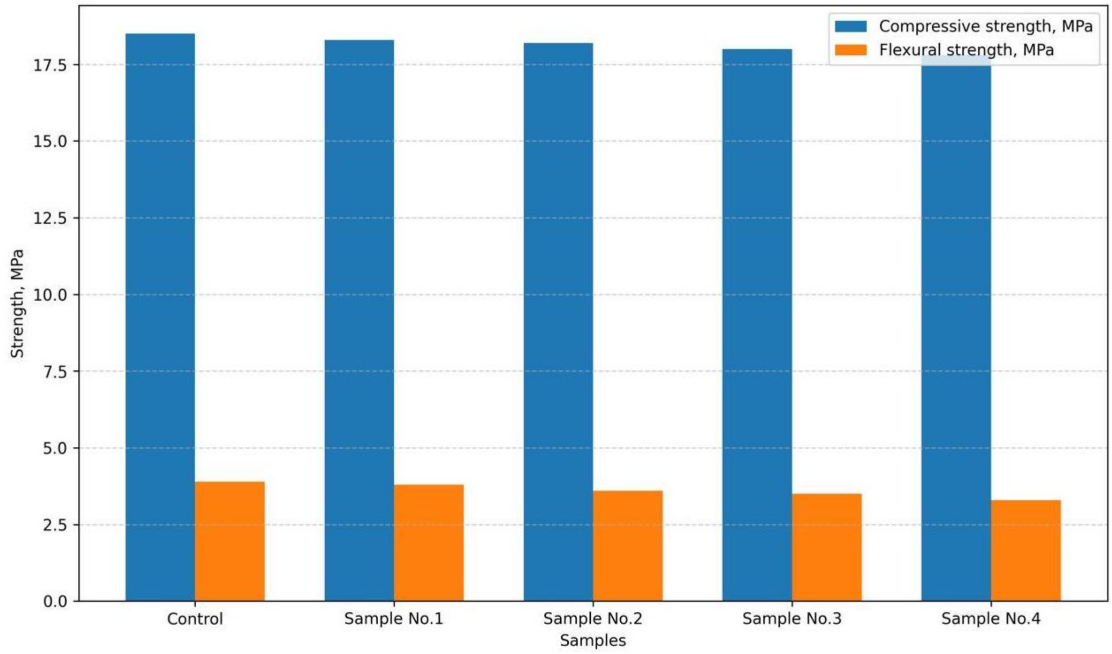

Fig. 4. Strength characteristics of silicate bricks (compressive and flexural strength) depending on the composition.

The control composition from 100% silicate mass has a compressive strength of 18–19 MPa and a flexural strength of 3.8–3.9 MPa, which is typical for industrial silicate bricks [3, 7]. With the introduction of glass powder and fly ash, there is a moderate decrease in strength, but it is smooth and controlled, in line with studies on the modification of autoclaved lime-silica materials with secondary silica-containing components [1, 4, 11].

In sample No. 1 (5% glass powder + 5% fly ash), compressive strength amounts to 18.2–18.3 MPa, practically identical to the control values. This indicates that with low degrees of substitution of the traditional silicate mass, the reactive silica glass powder can compensate for the reduced proportion of quartz sand due to its participation in hydrothermal reactions with the formation of calcium hydrosilicates [1, 12]. Similar conclusions were drawn in studies addressing the replacement of quartz sand with recycled glass, where the strength of silicate products remained the same or even increased with moderate dosages of glass [1, 4].

With a further increase in the content of glass powder and fly ash (sample No. 2), compressive strength reaches 17.8–17.9 MPa and flexural strength amounts to 3.6–3.7 MPa. These values remain at a level sufficient for the material to be used in the load-bearing and self-supporting walls of low- and medium-rise buildings, satisfying the requirements for silicate bricks in construction practice [3, 7].

World research has established that a 5–10% decrease in the density of autoclaved silicate materials usually results in a decrease in strength of no more than 5–10%, which is considered permissible, while thermophysical properties improve [6, 11, 13].

Sample No. 3 containing 10% glass powder and 15% fly ash shows a compressive strength of 17.6–17.7 MPa with a slightly lower density and lower thermal conductivity. Comparable results were reported in studies on lime–silica–fly ash autoclave systems, suggesting that optimal amounts of ash can contribute to the formation of a uniform fine-pore structure without a sharp deterioration of strength characteristics [14, 15]. In addition, the presence of aluminosilicate fly ash components can have a stabilizing effect on the microstructure of the C–S–H phase, partially compensating for the decrease in strength caused by increased porosity [9, 15].

A further decrease in strength in sample No. 4 is coupled with a reduction of compressive strength to 17.1–17.5 MPa and flexural strength to 3.3–3.4 MPa, which approaches the lower limit of operational feasibility for traditional silicate bricks. A similar trend has been widely described in literature: when the optimal content of secondary components is exceeded, the growth of porosity and the loosening of the structure begin to overpower the effects of additional hydrothermal phase formation, causing a more noticeable decrease in strength [6, 10, 11].

Therefore, compositions No. 2 and No. 3 can be deemed optimal in terms of performance balance. They provide:

- a significant decrease in thermal conductivity (approximately 25–30% compared to the control composition), which is consistent with the results of studies on the decrease in λ due to a controlled reduction of the density of autoclaved silicate materials [5, 8, 13];
- the preservation of compressive strength at at least 17.5 MPa to meet requirements for wall materials [3, 7];
- balanced density, strength, and water absorption, which is a key criterion when choosing materials for external enclosing structures in the operating conditions of HCS buildings [5, 16].

The obtained experimental data and their comparison with global studies confirm that the rational combination of glass powder and fly ash allows purposefully reducing the thermal conductivity of silicate bricks without a critical deterioration in strength characteristics, which makes such compositions promising for practical use in energy-efficient construction and the modernization of the housing stock.

3.3. Performance Indicators and Frost Resistance

Water absorption is one of the key performance indicators of wall materials, since it directly affects both the durability and the actual thermophysical characteristics of the enclosing structures in real operating conditions.

As can be seen from the experimental data (Fig. 5), the water absorption of the test silicate bricks ranges from 18.3 to 20.5% and follows a steady upward trend with an increase in the content of glass powder and fly ash. This behavior is natural and owes to an increase in total porosity and the share of capillary pores formed when the material density decreases.

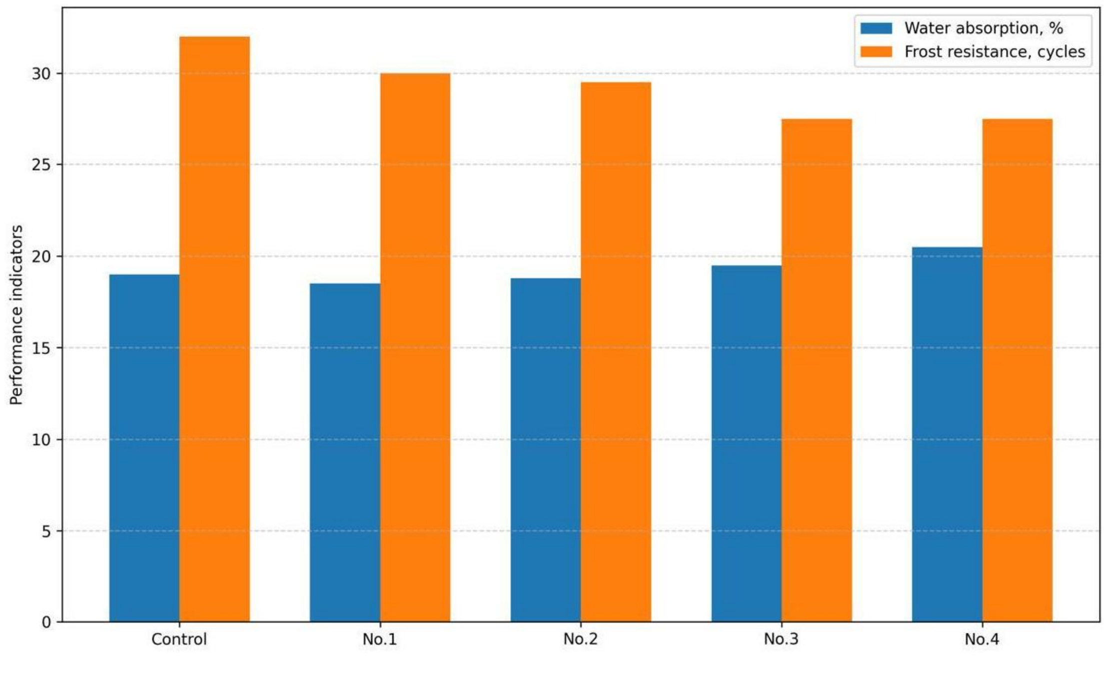

Fig. 5. Performance indicators (water absorption and frost resistance) of silicate bricks depending on the composition.

Similar relationships have been thoroughly described in the world literature for autoclaved lime-silica materials. It has been demonstrated that the decrease in average density due to the introduction of secondary silica-containing components or fly ash is almost always accompanied by an increase in water absorption, as a more developed system of open pores is formed [5-7]. Studies on modified sand-lime products have found that a 1–3% increase in water absorption in absolute value is typical with a 5–15% decrease in density and is not considered a critical factor, provided that frost resistance remains sufficient [3, 6].

Despite the increased water absorption, all the compositions tested in this study retain satisfactory frost resistance in the F27–F35 range, meeting the operational requirements for wall materials in the harsh continental climate of the Republic of Kazakhstan. This is a fundamentally important result, since in the classical view, higher water absorption can reduce frost resistance due to an increase in the volume of freezing water in the pores [4]. However, numerous studies indicate that the decisive factor in frost resistance is not absolute water absorption but the characteristics of the pore space – the ratio of open and closed pores, their size, and distribution [1, 11, 12].

Works devoted to autoclaved silicate and lime-ash bricks confirm that the presence of a finely porous and relatively uniform structure helps reduce internal stresses from freezing water and thus increases frost resistance even with moderately higher water absorption [7, 11]. Similar conclusions have been drawn for fly ash autoclave products, where the optimal amounts of ash have been shown to improve the pore structure and provide sufficient frost resistance despite higher water absorption compared to traditional silicate bricks [13, 14].

The behavior of compositions No. 2 and No. 3 is particularly notable, as they demonstrate an optimal balance between water absorption and frost resistance. With water absorption at about 18.6–19.5%, these compositions retain frost resistance of at least F27–F30, meeting operational requirements for the outer walls of residential buildings. Research emphasizes that it is this balance of indicators that is targeted in the development of energy-efficient wall materials: the permissible increase in water absorption is compensated by a decrease in thermal conductivity and the preservation of durability [3, 15].

It should also be borne in mind that in the real operational conditions of HCS buildings, the actual wetting of the masonry significantly depends on design solutions and protective measures (exterior decoration, hydrophobization, and the quality of joints). Studies of the operational humidity of brickwork show that in the presence of protective layers and under normal operation, even materials with 18–22% water absorption remain stable and do not show accelerated deterioration during freeze-thaw cycles [9, 10]. This further confirms the practical applicability of the developed compositions in the context of housing stock modernization.

Thus, the results obtained on water absorption and frost resistance agree well with modern scientific ideas about the behavior of autoclaved lime-silica materials. Compositions No. 2 and No. 3 have a rational combination of operational indicators, which makes them the most promising for use in external enclosing structures, provided that standard measures are taken to protect the masonry from moisture. This combination of properties confirms the possibility of purposefully increasing the energy efficiency of silicate bricks without compromising their durability and operational reliability.

3.4. Microstructure and Phase Composition (SEM and XRD) Compared to Testing Results

For an in-depth interpretation of the obtained physical, mechanical, and thermophysical characteristics of silicate bricks, our study used scanning electron microscopy (SEM) and X-ray phase analysis (XRD) data from open sources [11, 41] corresponding to the autoclaved systems most similar in composition and technology: "glass–lime" and "glass–lime–fly ash" (Fig. 6-9).

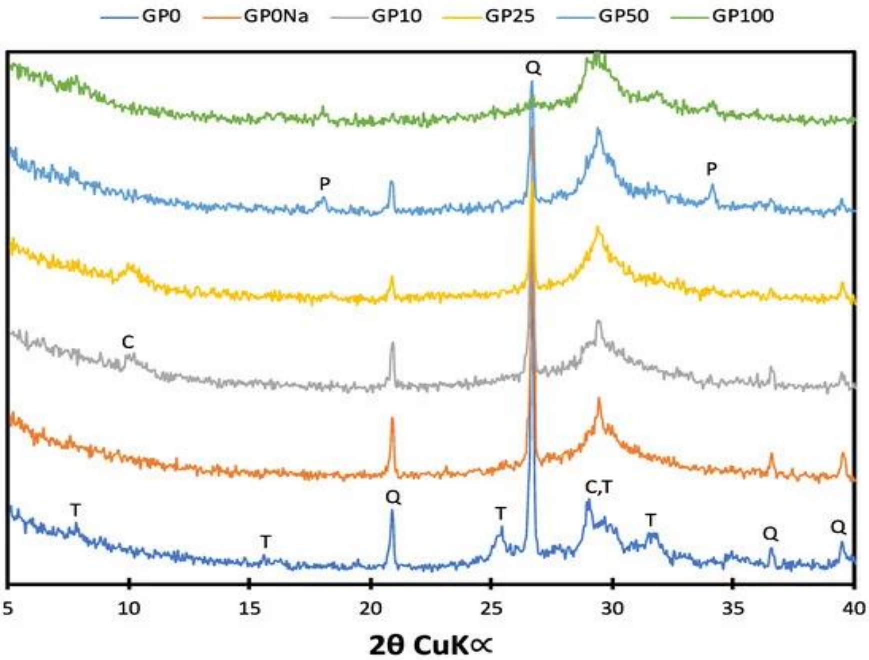

Fig. 6. X-ray diffraction pattern of an autoclaved silicate material of the "glass–lime" system (literary analogue). Identified phases: T — tobermorite (11 Å), Q — quartz, Cc — calcite, CH — portlandite. A wide diffuse halo in the range of 15–40° 2θ corresponds to the amorphous C–S–H phase forming the main matrix of the material. The X-ray phase pattern is characteristic of autoclaved lime silica systems using glass powder and is consistent with the data of the present study [11].

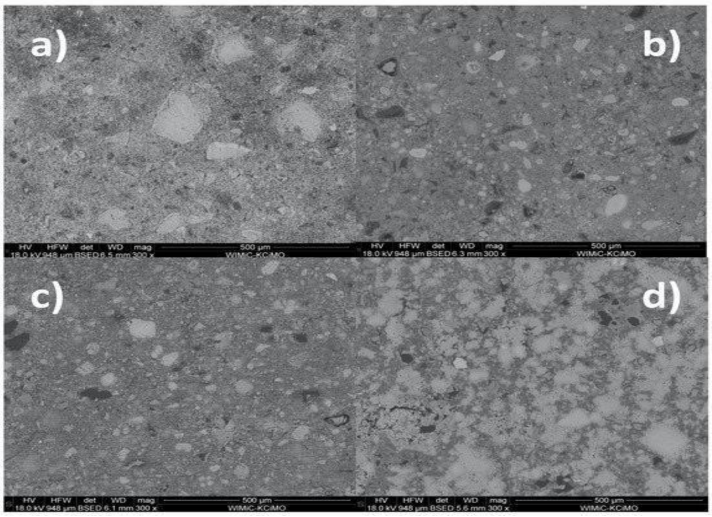

Fig. 7. SEM micrograph of the microstructure of an autoclaved silicate material of the "glass–lime" system (literary analogue). Laminar and lamellar structures of calcium hydrosilicates (C–S–H/tobermorite phases) are observed, forming a dense and uniform matrix. This microstructure preserves strength characteristics while reducing the average density of the material [11].

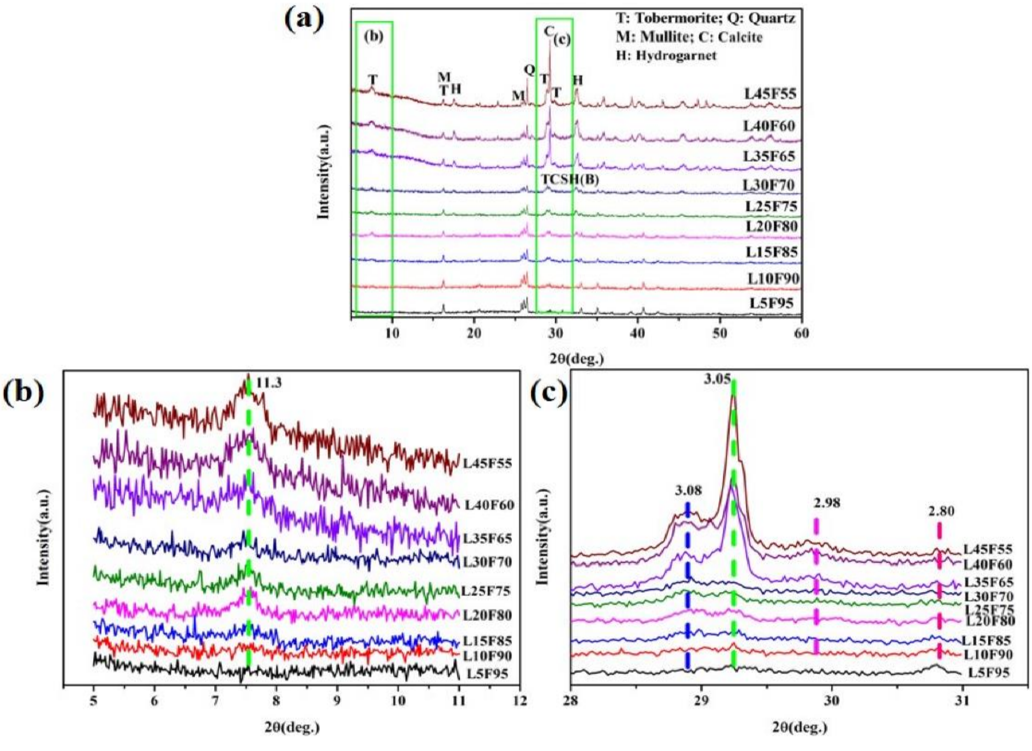

Fig. 8. X-ray diffraction pattern of an autoclaved material of the "glass–lime–fly ash" system (literary analogue). Identified phases: T – tobermorite, Q – quartz, Cc – calcite, CH – portlandite, and M – mullite, a relict phase of fly ash. The presence of a pronounced amorphous halo in the range of 15-40° 2θ indicates a significant share of poorly crystalline C–S–H phases affecting the thermophysical and strength properties of the material [41].

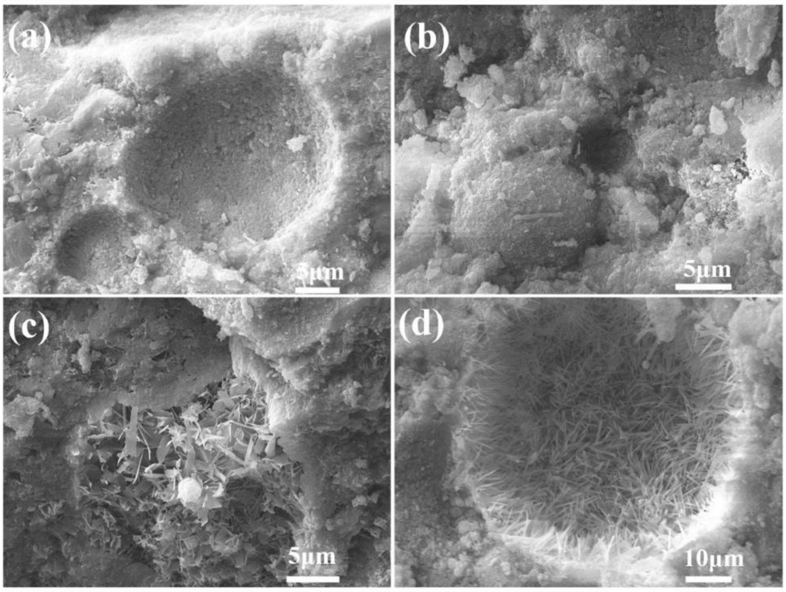

Fig. 9. SEM micrograph of the microstructure of the autoclaved material of the "glass–lime–fly ash" system (literary analogue). There are clearly visible needle-like and fibrous tobermorite crystals forming a spatial framework inside the pores and a gel-like C–S–H matrix. Such a microstructure explains the preservation of strength and frost resistance with reduced density in the optimal compositions No. 2 and No. 3 [41].

3.4.1. Phase Composition Analysis According to XRD

The X-ray diffraction patterns of autoclaved materials in Figs. 6 and 8 demonstrate a phase pattern typical of CaO–SiO_2–(Al_2O_3)–H_2O systems using glass and ash-slag components [11, 41]. Crystalline phases of tobermorite (11 Å), residual quartz, and the products of secondary processes – portlandite and calcite, formed during carbonization of $Ca(OH)_2$ – are observed in all cases.

A key feature of the XRD patterns is a pronounced diffuse amorphous halo in the range of 15–40° 2θ, corresponding to the poorly crystalline C–S–H phase, the proportion of which grows with an increase in the content of glass powder and fly ash [11]. The increase in the amorphous component explains the reduction of average density and thermal conductivity in compositions No. 2 and No. 3.

The X-ray diffraction patterns of the "glass–lime–fly ash" system (Fig. 8) also show mullite, which is a relict phase of fly ash [41]. Its presence indicates the partial inertness of ash and at the same time confirms its role as a source of the aluminosilicate component that stabilizes the hydrosilicate matrix.

3.4.2. Microstructural Features According to SEM

The SEM micrographs given in Figs. 2 and 9 visualize the microstructural mechanisms underlying the determined macroscopic properties. "Glass–lime" systems (Fig. 7) are characterized by the formation of a dense matrix of laminar and lamellar calcium hydrosilicates evenly distributed in the volume of the material [11].

Particularly notable are the micrographs of the "glass–lime–fly ash" system (Fig. 9) with clearly visible needle-like and fibrous tobermorite crystals forming the spatial framework inside the pores [41]. These structures effectively "reinforce" the C–S–H matrix and prevent microcracking, which explains the preserved compressive strength and satisfactory frost resistance of the experimental compositions.

3.4.3. Relationship between Microstructure and the Optimality of Compositions No. 2 and No. 3

The combined analysis of XRD and SEM data (Figs. 6–9) from open sources [11, 41] allows us to conclude that the optimal compositions No. 2 and No. 3 correspond to a state in which:

- tobermorite and the amorphous C–S–H phase are present in a balanced ratio;
- glass powder lowers the proportion of inert quartz, enhancing the reactivity of the system;
- fly ash stabilizes the aluminosilicate hydrate matrix;
- the obtained fine-pore structure reduces density and thermal conductivity without critical strength losses.

Thus, the microstructural and phase features of the literary analogues [11, 41] are fully consistent with the experimental results of this study and confirm the validity of the choice of compositions No. 2 and No. 3.

3.5. Practical Applicability for the Modernization of HCS Facilities

The obtained results have direct practical implications for the tasks of HCS modernization. The decrease in the thermal conductivity of silicate bricks by 0.20–0.35 W/(m·K) compared to traditional products allows for reducing heat loss through external walls without increasing their thickness or using additional insulation layers.

The use of the rational compositions No. 2 and No. 3 provides:

- improved energy efficiency of enclosing structures;
- reduced operating costs for building heating;
- the possibility of introducing the technology at existing silicate brick plants without significant modernization of the equipment;
- the utilization of glass cullet and fly ash, which reduces environmental pressure and complies with circular economy principles.

Therefore, the developed technology can be considered an effective engineering solution for the energy modernization of the housing stock, especially as part of the reconstruction and major maintenance of HCS buildings, where it is important to keep changes in structural schemes minimal and to maintain high technological compatibility with existing production lines.

4. CONCLUSIONS

1. The studies established that the rational use of glass powder and fly ash in the composition of autoclave silicate bricks makes it possible to purposefully reduce the average density and thermal conductivity of the material while maintaining the standard indicators of strength and operational reliability.

2. Samples No. 2 and No. 3 have been experimentally proven to be optimal in terms of thermophysical and physicomechanical characteristics, demonstrating 25–30% lower thermal conductivity compared to the control silicate brick with compressive strength not lower than 17.5 MPa, water absorption at 18.6–19.5%, and frost resistance above F27–F30.

3. The analysis of microstructural and phase characteristics of the "glass–lime" and "glass–lime–fly ash" autoclave systems based on SEM and XRD data has shown that the improvement of thermophysical properties is associated with the formation of a finely porous structure and a mixed hydrate matrix containing crystalline tobermorite and a significant proportion of the amorphous C–S–H phase, which provide balance between low density and the retention of strength.

4. Fly ash has been found to perform a stabilizing function in autoclaved silicate systems by participating in the formation of an aluminosilicate hydrate matrix and contributing to a uniform pore structure, which has a positive effect on the frost resistance of products.

5. The practical significance of the findings lies in the possibility of introducing the developed compositions at existing silicate brick factories without a drastic modernization of technological equipment, as well as in the simultaneous solution of the problems of recycling glass cullet and fly ash, increasing the energy efficiency of enclosing structures, and reducing operating costs in the HCS system.

Thus, the developed technology can be considered an effective engineering solution for the production of energy-efficient silicate bricks tailored to the modernization and renovation of the housing stock in a sharply continental climate.

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