



Controlling the density and thermal conductivity of silicate bricks by adjusting the dispersity of glass powder from glass waste

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Abstract. Under tightening requirements for the energy efficiency of buildings, the development of building materials with reduced thermal conductivity and with the use of secondary resources is gaining particular relevance. A promising area is the use of cullet in the production technology of silicate bricks as a wall building material. The aim of the study was to investigate the influence of dispersity and the content of glass powder obtained from sheet glass waste on the physicomechanical and thermophysical properties of autoclaved silicate bricks. Glass powder was examined as an active silica-containing additive and a source of alkaline Na⁺ ions that affect hydrothermal phase formation. The samples were molded by semi-dry pressing at a pressure of 20 MPa and 10–12% humidity of the mixture, after which the bricks were autoclaved according to the industrial regime of the silicate brick factory of West Kazakhstan Corporation of Building Materials, JSC (174–175°C, 0.8 MPa). The introduction of 5–15% fine glass powder was found to decrease the average density and thermal conductivity coefficient of the product while maintaining strength at the level of grades M150–M200. Microstructural and phase analysis showed a predominance of an amorphous and semi-crystalline C–S–H phase with the suppression of tobermorite formation due to the alkaline effect of glass powder. The study determined that the modification of silicate bricks with glass powder allows obtaining more energy-efficient wall materials without changing the industrial production technology. The findings testify to the prospects of recycling cullet in the silicate brick production technology with the aims of increasing the energy efficiency of the enclosing structures.

Keywords: silicate bricks, glass powder, dispersity, thermal conductivity, autoclaving, C–S–H, glass waste

Please cite this article as: Montayev S.A., Sakhiyev B.Zh., Ryskaliev M.Zh., Zharylgapov S.M., Montayeva A.S. Controlling the density and thermal conductivity of silicate bricks by adjusting the dispersity of glass powder from glass waste. *Construction Materials and Products*. 2026. 9 (3). 6. DOI: 10.58224/2618-7183-2026-9-3-6

1. INTRODUCTION

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Autoclave-cured silicate bricks remain one of the most popular wall materials due to their stable geometric parameters, environmental safety, and the accessibility of raw materials. However, traditional silicate products have a relatively high average density and thermal conductivity, which limits their application under the tightening requirements for the energy efficiency of buildings. Current trends in the development of building materials are focused on reducing heat loss through enclosing structures while maintaining standard strength and durability.

One of the effective approaches to controlling the structure and properties of autoclaved silicate materials is the introduction of active mineral additives capable of changing the kinetics of hydrothermal reactions. In this context, glass waste is of particular interest because it contains highly reactive amorphous silica and a significant amount of alkaline oxides, especially Na_2O . Fine glass powder can serve a double function, acting as an additional source of silica and at the same time producing an alkaline effect on the "lime – quartz sand – water" system.

Under autoclaving conditions, alkaline Na^+ ions accelerate the dissolution of silica-containing components and contribute to the formation of an amorphous and semi-crystalline phase of calcium hydrosilicates (C–S–H), while the formation of crystalline tobermorite can be suppressed. A number of studies show that such a transformation of the phase composition leads makes the matrix more compact, changes the pore structure, and, as a result, reduces thermal conductivity while maintaining or moderately increasing strength.

Despite the growing body of research on the use of glass powder in concretes and autoclaved cellular materials, the effect of the dispersity of glass powder on the properties of dense autoclaved silicate products, such as silicate bricks, remains underresearched. A particularly relevant task is to study the industrial modes of molding and autoclaving close to the conditions of existing factories.

The purpose of this study was to investigate the possibility of controlling the density, thermal conductivity, and strength characteristics of silicate bricks by varying the dispersity and content of glass powder made from glass waste while adhering to the same industrial production technology.

In recent years, the inclusion of technogenic waste in the composition of building materials has been viewed as one of the key tools for implementing sustainable development and circular economy principles and reducing the carbon footprint of the construction industry. Among the various types of recycled materials, glass waste is particularly noteworthy for its high silica content and significant potential of pozzolanic activity with the right fineness. Several studies indicate that glass powder from cullet can significantly modify the structure and properties of mineral composites for various purposes.

In particular, the modification clay soils and Siwalik clay with dispersed glass powder leads to a noticeable increase in compressive strength and an improvement of the engineering characteristics of the base [1]. The addition glass powder and construction waste to soils and stabilizing mixtures makes it possible to improve not only the mechanical characteristics but also the environmental indicators through the disposal of secondary materials [2, 3]. These results are important in terms of understanding how glass powder affects the structure and bearing capacity of porous mineral-bound systems.

Much research attention has been paid to the use of glass powder and crushed glass in concrete and cement composites. Overviews suggest that the substitution of a part of natural sand or cement with glass waste of various dispersity allows improving a number of mechanical characteristics, as well as reducing the environmental impact of production [4, 5]. In particular, glass powder used as a pozzolanic additive in Portland cement systems can increase their modifying efficiency with optimal grinding fineness and dosage [6]. In ultra-high-performance concrete (UHPC), replacing part of the cement with fine glass powder provides a combination of high strength and improved environmental performance due to a decrease in the clinker component [7-10].

Modern research expands the range of objects in which glass powder can be used: from ancient concretes and mortars to semi-flexible coatings and high-strength cement mortars [11, 12]. Research findings show that the combination of glass powder with agricultural waste ash, the ash of date palm seeds, and other technogenic components achieves a synergistic effect in improving strength, rheological characteristics, and environmental resistance [11, 12]. A number of studies have investigated the effect of treating the surface of glass particles with silanes and other modifiers, which provides an improvement of the water resistance, freeze-thaw resistance, and durability of concrete composite materials [13].

A separate line of research deals with the transition from the micrometer to the nanometer level dispersity of glass powder. Research has found that the transformation of glass waste into nano-powder achieves a sharp increase in the specific surface area and reactivity, which contributes the intensive formation of hydration products and the compaction of composite structure [14]. This trend confirms the key role of glass powder dispersity as a control parameter for the structure and properties of materials.

With the continuing advancement of glass recycling technologies, the possibility of incorporating glass powder in bricks and wall materials is being actively investigated. Studies have shown that replacing some of the traditional raw materials in clay and composite bricks with crushed glass and fiberglass results in increased compressive strength, changes in the porous structure, and improved thermophysical characteristics [15-23]. The use of contaminated glass dust in fired clay bricks has been found to improve the strength and performance properties of the product while also allowing to utilize complex waste [19]. The addition of glass powder together with plant or technogenic additives allows optimizing the thermophysical and mechanical properties of bricks, although research emphasizes that the dosage and granulometry of glass need to be controlled to avoid the deterioration of strength and freeze-thaw resistance [21, 23].

Particularly notable are works that approach glass powder not only as an inert aggregate but also as an active mineral additive involved in forming the structure of the binder matrix. Multi-criteria optimization approaches used to boost the activity of glass in mortars and concretes demonstrate that with the right fineness of grinding and heat treatment modes, a balance can be struck between the strength, density, thermal conductivity, and durability of materials [6, 24]. In UHPC, it has been found that cement can be replaced with glass powder at high rates without the loss of strength with sufficient dispersity and reactivity of the glass phase [7-9].

Important advancements have been made in modeling methods, particularly genetic programming and other machine learning algorithms for predicting the strength and deformation characteristics of materials with the addition of glass powder [16, 25]. These approaches allow quantifying the contribution of glass dispersity and content to the properties of the composite and identifying optimal combinations of parameters for a given level of performance.

Against the background of the active study of glass powder, we must note a parallel line of research concerning the use of other waste and light aggregates, such as expanded clay and expanded clay dust [10, 22, 23, 26-28]. It has been demonstrated that expanded clay production wastes with a developed porous structure and aluminosilicate composition can be used as active mineral additives and light aggregates, providing a decrease in the density of concrete and brick, improved thermal insulation properties, and reduced environmental pressure [22, 23, 26-28]. Studies on lightweight concretes and lightweight self-compacting expanded clay concretes demonstrate the possibility of achieving high strength at low density, which is important for creating energy-efficient enclosing structures [23, 26-28].

Summary overviews on modern wall materials and bricks emphasize a steady transition from traditional compositions to composites using technogenic waste, secondary resources, and active mineral additives [27-30]. The most attention is paid to concrete, porous ceramic materials, light concrete, and fired bricks. However, autoclaved silicate bricks, despite their widespread industrial use, remain a relatively understudied object in terms of the comprehensive recycling of cullet and the influence of glass powder dispersity on their thermophysical properties and structure.

Thus, our analysis of current literature shows that:

- the effect of glass powder on the mechanical, microstructural, and durability characteristics of concretes and mortars has been well studied [1, 4-9, 11-14, 20, 25, 31];
- the possibility of controlling porosity, thermal conductivity, and density by changing the composition and structure of the material has been demonstrated on various types of bricks and porous materials based on industrial and agricultural waste [16, 19-23, 26, 32];
- the active development of lightweight concretes and composites using expanded clay and other pore-forming additives supports the importance of optimizing material structure to improve energy efficiency [22, 23, 26-28];

• meanwhile, comprehensive research of the effect of specifically the dispersity of waste glass powder on the density, thermal conductivity, microstructure, and strength of autoclaved silicate bricks is virtually non-existent in the available literature.

The identified gap in research determines the relevance of the present study aimed at establishing quantitative relationships between the dispersity of glass powder and the performance characteristics of silicate bricks, as well as at advancing the concept of energy-efficient autoclaved wall materials based on technogenic raw materials.

2. METHODS AND MATERIALS

2.1. Raw Materials

The main raw material used in the study was a factory silicate mass used by *West Kazakhstan Corporation of Building Materials, JSC* (Uralsk, Kazakhstan) in the production of autoclave-cured silicate bricks. The silicate mass included quartz-feldspar sand and building quicklime. The lime met the requirements of GOST 9179, and the content of active oxides ($\text{CaO} + \text{MgO}$) was no less than 90%.

Glass powder obtained from scrap sheet glass was used as the mineral additive. The preparation of glass powder involved crushing the glass waste, followed by fine grinding. Three fractions differing in median particle size were made for the study: $d_{50} \approx 10\text{--}20$, $20\text{--}40$, and $30\text{--}50$ μm . The glass powder was characterized by a high content of amorphous silicon dioxide and the presence of alkaline oxides, mainly Na_2O , which ensured its reactivity and alkaline effect on the $\text{CaO}\text{--}\text{SiO}_2\text{--}\text{H}_2\text{O}$ autoclaved system without adding additional activators.

2.2. Mixture Compositions and Experiment Design

The design of the experiment included a control composition without glass powder and three modified compositions, differing in the mass fraction and dispersity of glass powder. Glass powder was introduced by partially replacing the silica-containing component in the factory silicate mass while maintaining the basic lime formula.

The glass powder content was 5, 10, and 15% of the weight of dry components. The moisture content of the moldable mixture was maintained in the range of 10–12%. Table 1 presents the tested compositions.

Table 1. Mixture compositions (wt.% of dry components).

Composition number	Factory silicate mass (sand+lime), %	Glass powder, %	d_{50} of glass powder, μm	Water (to dry matter), %
Control	100	0	–	10–12
1	95	5	30–50	10–12
2	90	10	20–40	10–12
3	85	15	10–20	10–12

2.3. Mixture Preparation and Sample Molding

The dry components were dosed by weight and mixed to a uniform mixture. After adding the calculated amount of water, the mixture was further mixed and rested for 5–10 minutes to allow moisture to distribute evenly and to stabilize the structure of the semi-dry mass.

The samples were molded by semi-dry pressing at 20 MPa. For different types of tests, the following geometric shapes of samples were used:

- compressive strength – cylindrical samples with a diameter of 50 mm and a height of 50 mm ($\text{Ø}50 \times 50$ mm);
- flexural strength – prism-shaped samples measuring $40 \times 40 \times 160$ mm.
- The study used at least 5 samples of each composition for compressive strength tests and 3 for flexural and thermal conductivity tests.

2.4. Autoclave Curing

The tested samples were autoclave-cured according to the industrial regime adopted at the silicate brick factory (Uralsk, Kazakhstan):

- raising the temperature to 174–175°C over 1.5–2 hours;
- isothermal exposure at a temperature of 174–175°C and a saturated steam pressure of about 0.8 MPa for 6–8 hours;
- cooling to atmospheric pressure for about 2 hours;
- after autoclaving, the samples were cooled and rested to stable temperature and weight under laboratory conditions.

2.5. Physical and Mechanical Tests

The average density, water absorption, compressive strength, and flexural strength were determined per the requirements of Kazakhstan standards (GOST in force in the Republic of Kazakhstan) for silicate bricks and autoclave-cured stones.

Compression tests were performed on cylindrical samples Ø50×50 mm, and flexure tests were carried out on prisms measuring 40×40×160 mm. The design values were the averaged results of a series of tests.

Freeze-thaw resistance was determined by the cyclic freeze-thaw method in accordance with national regulations for silicate products, recording the loss of weight and/or strength after the given number of cycles.

2.6. Determination of Thermal Conductivity

The thermal conductivity coefficient λ was determined on samples dried to constant weight with an ITP-MG4 device by the steady-state method under a steady-state heat flux. The tests were performed at room temperature. At least three measurements were recorded for each composition to calculate the average λ .

2.7. Microstructural and Phase Analysis

The microstructure of the autoclaved samples was examined on fresh chips by scanning electron microscopy (SEM) using a Hitachi TM4000 Plus microscope. Additionally, localized elemental analysis (EDS) was performed to examine the distribution of silica and alkaline components in the matrix.

X-ray diffraction analysis was conducted on a DRON-3 automated diffractometer with $\text{CuK}\alpha$ radiation and a β filter. The setup was as follows: $U=35$ kV; $I=20$ mA; θ - 2θ range; scan rate of $2^\circ/\text{min}$. Semi-quantitative X-ray diffraction analysis was conducted on the diffractograms of powder samples following the method of equal samples and artificial mixtures.

Phase composition was determined by X-ray diffraction (XRD). Diffractogram analysis was conducted to identify crystalline phases (quartz and tobermorite) and to evaluate the contribution of the amorphous and semi-crystalline C-S-H phase typical of autoclaved silicate systems with an alkaline influence.

3. RESULTS AND DISCUSSION

3.1. Effect of Glass Powder Dispersity on Average Density

The average density of the autoclaved samples of silicate bricks follows a steady downward trend with an increase in the proportion and a decrease in the dispersity of glass powder (Fig. 1). The greatest reduction of density is observed when using glass powder with $d_{50} \approx 10\text{--}20$ μm in an amount of 10–15%.

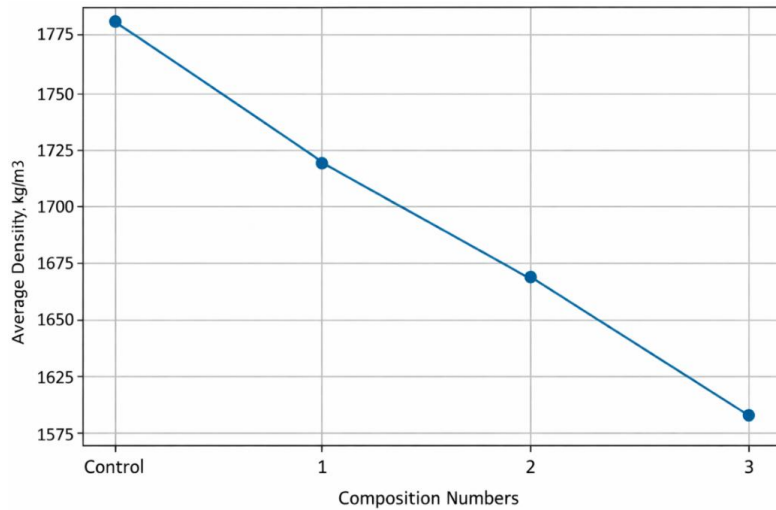


Fig. 1. Effect of dispersed glass powder on the average density of samples.

The obtained average density of autoclaved silicate brick samples (Fig. 1) shows a clear dependence of this indicator on the content and dispersity of glass powder. Compared with the control composition, with the introduction of 15% glass powder with $d_{50} \approx 10\text{--}20\ \mu\text{m}$, average density decreases from $1780\ \text{kg/m}^3$ to $1580\ \text{kg/m}^3$, meaning a relative decrease of $\sim 11\%$.

Similar trends of reduced density using fine glass waste have been reported for various mineral composites and brick materials [16, 19–21]. However, most published works consider glass powder mainly as a partial substitute for the aggregate. Our study shows that under autoclaving conditions, glass powder serves as an active mineral additive that changes the structure formation mechanism.

The observed density reduction comes from a combined effect of the pozzolanic activity of amorphous SiO_2 glass powder and the alkaline effect of Na^+ ions, which speed up the dissolution of silica and facilitate the formation of calcium hydrosilicates [6, 24, 29]. A similar effect has previously been noted in autoclaved systems with alkaline modification of the phase composition [30].

3.2. Thermal Conductivity and its Relationship to Density and Microstructure

The measurements of thermal conductivity with the ITP-MG4 device show that the decrease in λ is more pronounced than the reduction of density (Fig. 2), indicating **a qualitative change in the structure of the pore space**.

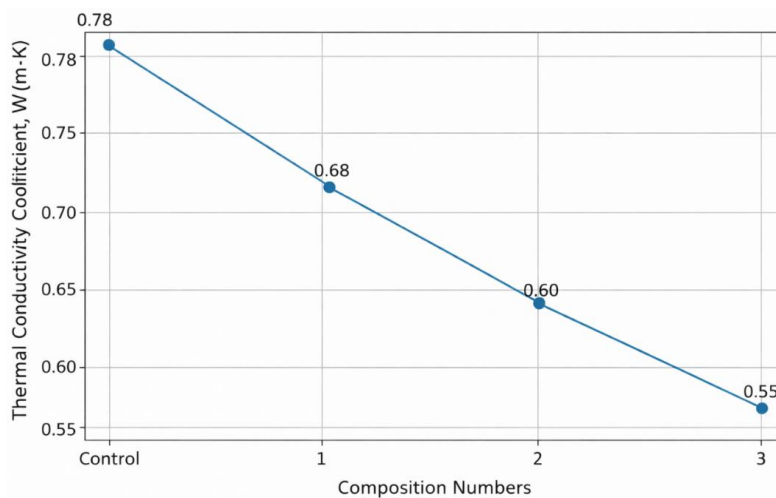


Fig. 2. Dependence of the thermal conductivity coefficient of silicate bricks on the dispersity of glass powder.

Changes in the thermal conductivity coefficient λ (Fig. 2) are more pronounced compared to the decrease in average density. With a 7–11% decrease in density, thermal conductivity is reduced by up to 23–30%, which indicates a qualitative change in the structure of the material rather than just an effect of lower weight.

The thermal conductivity of composition S-15-20 lowered from 0.78 to 0.55 W/(m·K), reaching the level of energy-efficient wall materials. Similar λ values have been reported previously for bricks and composite materials modified with glass powder and plant or mineral additives [21-23, 26].

The significant decrease in thermal conductivity is explained by the redistribution of the pore structure: an increased share of small capillary and gel pores and a smaller number of through macropores responsible for the convective component of heat transfer. Similar conclusions have been reached in research on the management of the thermophysical properties of bricks and light concretes based on technogenic waste [22, 23, 26-28].

Thus, the dispersity of glass powder acts as a key parameter for controlling the thermophysical characteristics of silicate bricks, agreeing with the concept of multi-criteria optimization of the properties of mineral composites [24].

3.3. Strength Characteristics (Compressive and Flexural Strength)

Despite the reduced density, the strength characteristics of the samples remain at the standard level (Fig. 3).

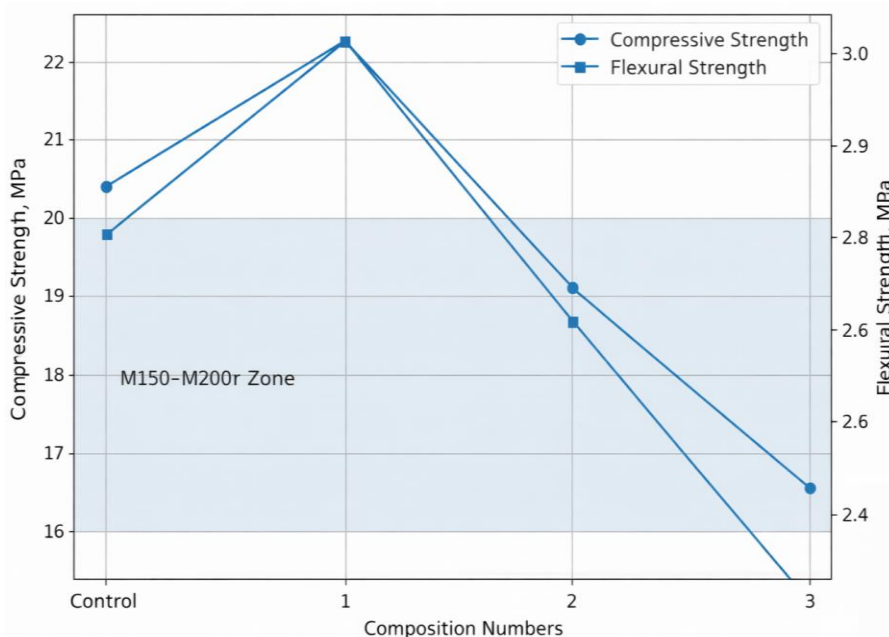


Fig. 3. Effect of glass powder content and dispersity on the compressive and flexural strength of autoclaved silicate bricks.

Comparing compressive strength and average density (Fig. 3), we can identify a fundamentally important engineering effect: the decrease in density and thermal conductivity is not accompanied by the loss of standard strength.

Compressive strength varies in the range of 16.5–22.3 MPa, corresponding to grades M150–M200 according to Kazakhstan standards for silicate bricks. Maximum strength is reached with a moderate content of glass powder ($\approx 5\%$), which is explained by the compaction of the structure due to the additional formation of the C–S–H phase, similar to the effects described for cement and autoclaved systems [4, 7-9].

When the content of glass powder is increased to 12–15%, strength decreases slightly but remains in the acceptable range for wall materials. A similar trade-off between density reduction and strength

retention has previously been noted in bricks and concretes using glass waste and other active additives [16, 19, 22].

In this way, a rational engineering balance is achieved between mechanical reliability and energy efficiency, satisfying current requirements for wall materials [27].

3.4. Water Absorption and Freeze-Thaw Resistance

The water absorption of samples with fine glass powder does not exceed standard values, falling in the range of 16-19%. At the same time, pore redistribution leads to an increase in freeze-thaw resistance (Fig. 4).

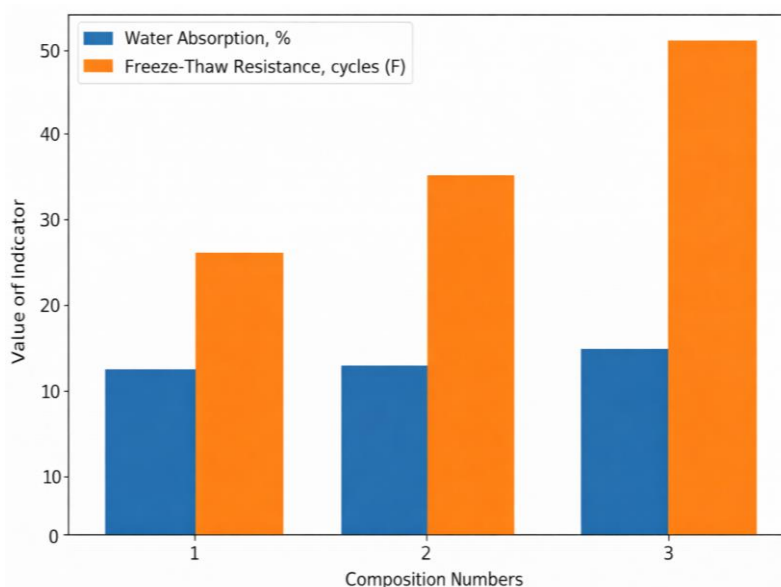


Fig. 4. Effect of glass powder dispersity and content on the water absorption and freeze-thaw resistance of autoclaved silicate bricks.

The introduction of fine glass powder leads to a moderate increase in water absorption (up to 16–19%), but this indicator does not exceed the standard values for silicate bricks. Similar behavior is noted in studies of bricks and concretes with a redistributed pore structure [21, 26]. Meanwhile, the freeze-thaw resistance of the samples grows from F25 in the control composition to F50 in the S-15-20 composition. The increase in freeze-thaw resistance is due to a reduced proportion of large open pores and a more uniform distribution of moisture in the microporous structure, which curbs internal stresses during freeze-thaw cycles. Similar durability mechanisms have previously been described for lightweight concrete and bricks using technogenic additives [23, 27, 28].

3.5. Microstructural and Phase Analysis Interpretation (SEM and XRD)

Micrographs in Fig. 5 illustrate the evolution of the microstructure of autoclaved silicate bricks. Particularly representative is the SEM image of fine waste glass powder with angular particle morphology and smooth fracture surfaces (reproduced according to Odaa et al. [14]).

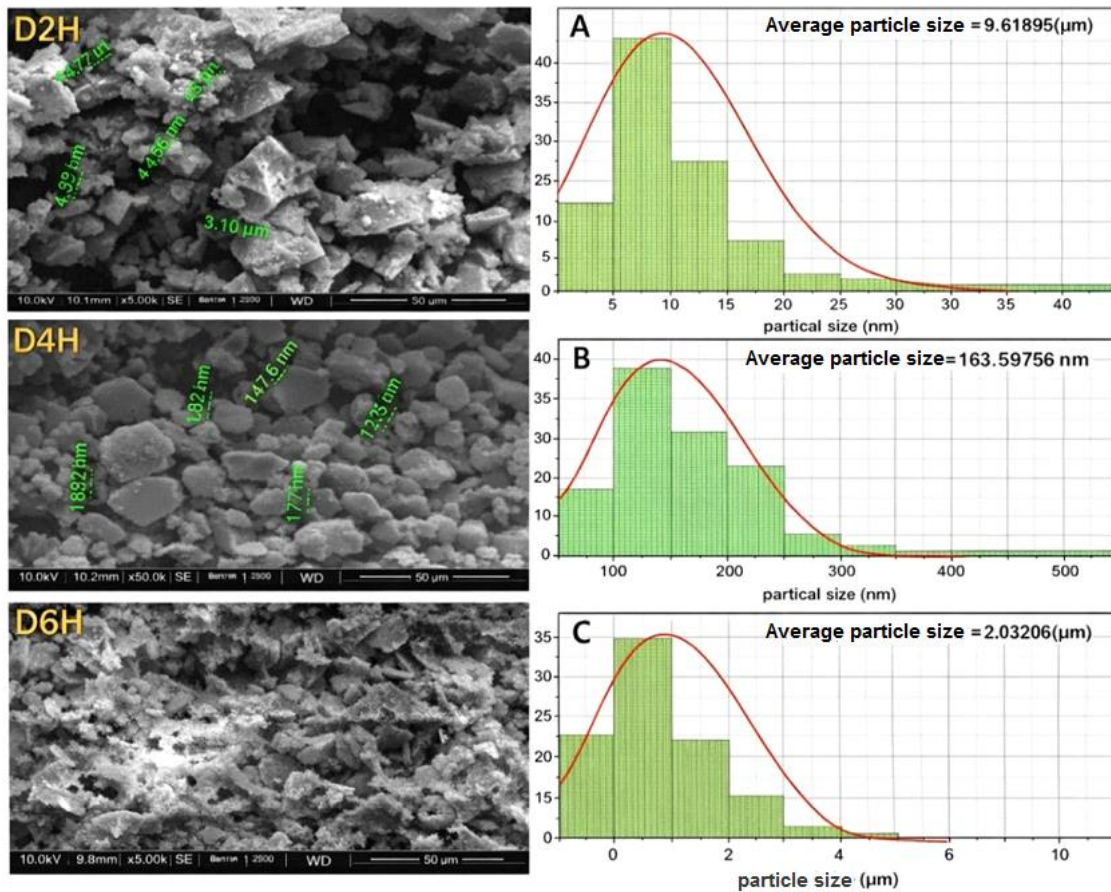


Fig. 5. Microstructure of crushed glass and distribution of glass powder particles (A, B, and C) in FE-SEM images (D2H, D4H, and D6H), respectively, according to Odaa et al. [14].

This morphology intensifies the dissolution of silica under alkaline hydrothermal conditions, which explains the predominance of the amorphous and semi-crystalline C–S–H phase observed in the modified samples of silicate bricks (Fig. 6(a)). In contrast to the control composition with well-developed laminar crystals of tobermorite (Fig. 6 (b)), the introduction of fine glass powder leads to the formation of a denser and more uniform matrix, which is consistent with the reduced thermal conductivity and the increased frost-thaw resistance of the material.

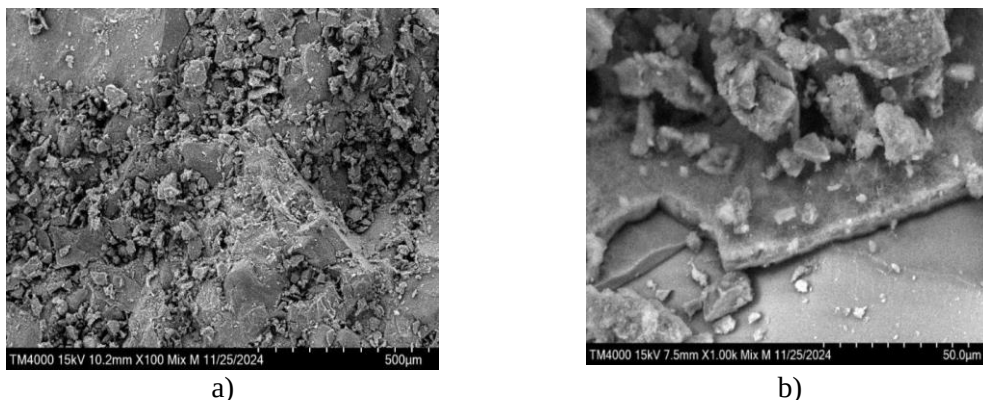


Fig. 6. Microstructure of samples with the addition of fine glass powder (a) and the control sample (b) of silicate bricks.

The results of SEM studies show that glass powder is almost fully engaged in hydrothermal reactions. In the structure of the modified samples, the grains are densely enveloped with hydration products, leaving no pronounced intergranular boundaries, which is typical for systems with the intensive formation of the C–S–H phase [14, 31].

X-ray diffraction analysis (XRD) data show a decrease in the intensity of peaks characteristic of tobermorite and a simultaneous increase in the amorphous background in the range of $26\text{--}32^\circ 2\theta$ corresponding to the amorphous and semi-crystalline C–S–H phase (Fig. 7).

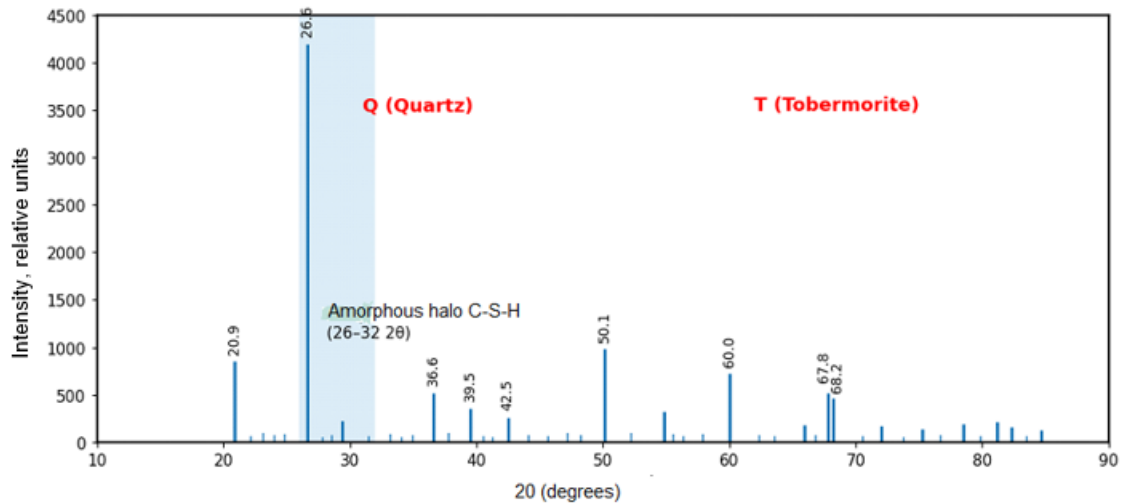


Fig. 7. X-ray diffraction diagram of autoclaved silicate bricks with the addition of fine glass powder. The main crystalline phases indicated are quartz (Q) and tobermorite (T). The semitransparent region shows an amorphous halo of the C–S–H phase in the range of $26\text{--}32^\circ 2\theta$. The values of 2θ angles are shown above the intensity reflexes.

As can be seen from Fig. 7, the phase composition of the sample is distinguished by a predominance of quartz and trace amounts of tobermorite. This indicates the suppression of tobermorite crystallization by alkaline Na^+ ions from glass powder and the stabilization of the less crystalline calcium hydrosilicates, consistent with previously published data on autoclaved systems [29, 30].

Similar patterns of the effect of alkaline ions and dispersed amorphous silica on phase formation in autoclaved silicate systems have been established previously in fundamental studies of hydrothermal C–S–H systems and autoclaved materials [29, 30].

The conceptual model of this process, as depicted in Fig. 6, is in good agreement with the results of phase and microstructural analyses.

The results confirm that adjusting the dispersity of waste glass powder allows purposefully controlling the density, thermal conductivity, and strength characteristics of silicate bricks without modifying the basic industrial production technology.

The optimal solution is to use 10–12% of glass powder with $d_{50} \approx 20\text{--}40\ \mu\text{m}$, which achieves a decrease in thermal conductivity to $0.55\text{--}0.60\ \text{W}/(\text{m}\cdot\text{K})$, maintains strength at the level of M150–M175, and raises freeze-thaw resistance to F35–F50. This approach fully aligns with current trends in the development of energy-efficient wall materials and sustainable construction [27–30].

The conceptual diagram given in Fig. 8 illustrates the effect of glass powder as a source of reactive SiO_2 and alkaline Na^+ ions on the kinetics of hydrothermal reactions. The alkaline effect intensifies the dissolution of silica and the formation of an amorphous semi-crystalline C–S–H phase while simultaneously suppressing the crystallization of tobermorite. This influence results in the compaction of the material with the formation of a microstructure and a decrease in its thermal conductivity.

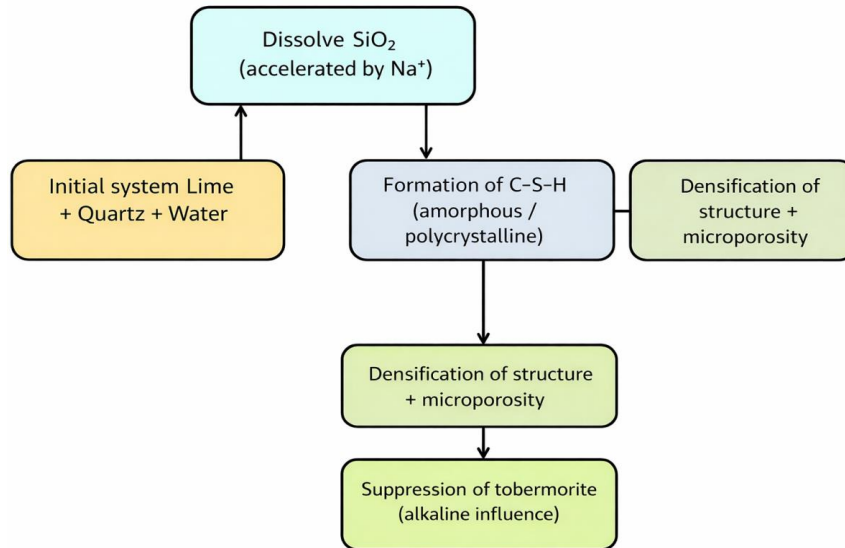


Fig. 8. Conceptual model of phase transformations in autoclaved silicate systems with the addition of glass powder.

4. CONCLUSIONS

The study investigated the influence of the dispersity and content of glass powder obtained from sheet glass waste on the physical, mechanical, and thermophysical properties of autoclaved silicate bricks made by the standard industrial technology.

It has been found that the introduction of 5–15% glass powder into the silicate mass makes it possible to purposefully control the structure and performance of the material without changing the modes of molding and autoclave curing. The most pronounced effect was achieved using fine glass powder with a characteristic particle size of $d_{50} \approx 20\text{--}40\ \mu\text{m}$.

The key results of the study can be summarized as follows:

1. The introduction of glass powder leads to a 4–11% decrease in the average density of silicate bricks compared to the control composition due to the intensification of hydrothermal reactions and a change in the pore structure of the material.
2. The thermal conductivity coefficient lowers by 13–30% depending on the dispersity and content of glass powder, and the decrease in thermal conductivity is more pronounced than the reduction of density, suggesting a qualitative redistribution of the pore space.
3. The strength characteristics of modified samples remain at the standard level of grades M150–M200. The optimal compositions achieve a favorable compromise between reduced thermal conductivity and sufficient bearing capacity, which is especially critical for energy-efficient wall materials.
4. The water absorption and freeze-thaw resistance of the modified bricks satisfy current standard requirements, and a number of compositions show increased freeze-thaw resistance due to a more uniform distribution of moisture in their microporous structure.
5. SEM and XRD results confirm that glass powder is actively involved in hydrothermal reactions. Alkaline Na^+ ions from the glass inhibit the crystallization of tobermorite and stabilize the amorphous semi-crystalline C–S–H phase, thus creating a dense but microporous matrix responsible for the lower thermal conductivity.

Thus, adjustment of the dispersity of waste glass powder proves to be an effective tool for controlling the structure and thermophysical properties of autoclaved silicate bricks. The obtained findings confirm the prospects of industrial utilization of cullet in the production technology of silicate products and can be applied in the development of energy-efficient enclosing structures for modern construction.

5. ACKNOWLEDGEMENTS

The research was carried out in the framework of program-targeted funding by the Ministry of Science and Higher Education of the Republic of Kazakhstan on the topic: BR24993125 "Rational technology of using cullet in the production of silicate bricks to increase the thermal protection of enclosing structures during the modernization of housing and communal services facilities".

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