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Article

Effect of waste glass powder particle size, content, and compaction pressure on the properties of autoclaved silicate brick

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Abstract. The present study evaluates the influence of waste glass powder particle size distribution, dosage, and compaction pressure on the performance of autoclaved silicate brick. Glass powder produced from container glass waste was incorporated into a quartz–lime mixture at 5, 10, and 15 wt.% in four fractions: ≤63, 63-140, 140-315, and 315-630 μm. The specimens were formed by semi-dry pressing and subjected to autoclave curing. Their average density, compressive strength, water absorption, thermal conductivity, and frost resistance were then determined. The results demonstrated that the modifying effect of glass powder strongly depends on its dispersity. The most favorable performance was obtained with the finest fraction (≤63 μm) at 10 wt.% and 10 MPa compaction pressure, where the average density reached 1860 kg/m^3, compressive strength 14.5 MPa, water absorption 11.3%, and thermal conductivity 0.77 W/(m·°C). Coarser fractions showed a progressively weaker effect, and the 315–630 μm fraction was unfavorable relative to the reference composition. Frost resistance remained at F50 for all specimens. Increasing compaction pressure from 5 to 15 MPa enhanced densification and strength development while only slightly changing thermal conductivity. The results confirm the potential of finely ground waste glass as an effective modifying additive for silicate brick production.

Keywords: autoclaved silicate brick, waste glass powder, particle size distribution, compaction pressure, compressive strength, water absorption, thermal conductivity.

1. Introduction

Silicate brick remains an important wall material because it combines relatively simple raw materials with hydrothermal curing, and its service properties are governed not only by composition but also by particle packing, molding pressure, and phase formation during autoclaving [1]. Interest in this material has grown further in the context of sustainable construction, since sand-lime products can serve as a platform for incorporating industrial by-products and recycled mineral components without abandoning established production technology [2]. At the same time, conventional silicate products still face a practical materials challenge: their overall performance must be improved in a balanced way, because strength, density, water absorption, thermal conductivity, and durability are interrelated rather than independent characteristics [3].

One of the most promising approaches is the use of waste glass, since soda-lime glass is rich in amorphous silica and can act not only as an inert filler but also as a reactive component under alkaline and hydrothermal conditions [4]. Finely ground glass is known to exhibit pozzolanic reactivity, and its activity increases as particle size decreases because the specific surface area rises and the amorphous network becomes more accessible to dissolution and secondary hydrate formation [5]. The ability of glass powder to react with calcium-bearing systems has also been confirmed in studies showing that it can consume portlandite and contribute to the formation of

additional binding phases, which explains why the particle size of the glass component often becomes a key technological variable rather than a secondary parameter [6].

In autoclaved sand-lime systems, this issue is especially important because replacing part of the quartz component with glass changes both the kinetics of hydrothermal reactions and the resulting pore structure. [2] reported that glass sand can improve the compressive strength of autoclaved products relative to traditional silicate units, linking this effect to the altered course of hydrothermal synthesis and the formation of a favorable microstructure. In a later study, the same research group showed that glass-containing autoclaved bricks differ from conventional ones not only in strength but also in reaction temperature, phase assemblage, and bond formation, confirming that amorphous glass behaves differently from crystalline quartz during processing [3]. Pore-structure analysis of autoclaved materials modified with glass sand further demonstrated that the glass component can substantially change the distribution and character of pores, which is directly relevant to water absorption and density [7].

At the same time, the literature does not support a universally positive effect of glass addition, and this makes optimization necessary. [6], who examined autoclaved silica-lime materials made with different waste container glasses, found that the type of glass and the resulting structure strongly influenced density, water absorption, and strength, so the benefit of glass incorporation depended on the specific formulation rather than on the fact of replacement alone [8]. Similar non-monotonic behavior is also seen in related autoclaved systems modified by other mineral wastes. For example, basalt powder in sand-lime products showed the best results at around 10% addition, while higher dosages became less favorable [9]. A later microstructural study of basalt-modified autoclave brick confirmed that moderate waste additions can improve performance, whereas excessive replacement disrupts the optimal structure formation pathway [10]. In the same way, mixture-design work on sand-lime bricks produced with coal tailings showed that strength responds sensitively to raw-material proportions, so there is a narrow compositional window in which desirable properties are maximized [11].

The role of particle size is equally unresolved in the broader brick literature. In fired bricks containing waste glass, [12] showed that glass particle size significantly affects density, water absorption, compressive strength, and thermal conductivity, and that not every increase in fineness is beneficial. [13] also reported that waste glass can increase compressive strength and decrease water absorption in brick materials, but the magnitude of the effect depends on dosage and the way the glass modifies porosity. [14] found an optimum replacement level for waste glass powder in fired bricks rather than a linear improvement with increasing content, which again points to the need for dosage optimization. [12], [13], [14] are not directly transferable to autoclaved silicate brick, but they consistently show that glass content and dispersity control the balance between densification, reactivity, and pore development.

Thermal performance adds another layer to the problem. In some sand-lime systems, porous glass-based additives markedly reduce thermal conductivity by lowering density and increasing closed porosity. In contrast, [15] observed in fired clay bricks with waste glass sludge that denser microstructures created by glass addition can improve strength while increasing thermal conductivity, showing that the thermal effect of glass is system-specific and must be interpreted together with density and pore structure [16]. Autoclaved lime-based bricks produced from fly ash, sand, and lime also demonstrate that forming pressure has a direct effect on density, compressive strength, water absorption, and thermal conductivity, which means that raw-material optimization alone is insufficient if technological parameters are not considered simultaneously [1]. Likewise, autoclaved lime-saline soil bricks exhibited property changes that depended strongly on composition and processing, including durability behavior under freezing and thawing [16].

Therefore, the current research problem is not simply whether waste glass can be used in silicate brick, but what particle size distribution, dosage, and compaction pressure provide the best combined set of physical, mechanical, thermophysical, and durability properties in an autoclaved quartz-lime system. Existing studies [2], [3], [8] confirm the relevance of glass waste utilization in sand-lime materials, but they do not sufficiently resolve the combined influence of fractional

particle size distribution, moderate glass content variation, and semi-dry compaction pressure within one experimental program. This gap is practically important because an additive that lowers water absorption may not necessarily maximize strength, and a denser structure may not automatically give the most favorable thermal conductivity.

Against this background, the present study aims to determine how the fraction size of powdered glass waste, its content in the silicate mixture, and the applied compaction pressure influence the comprehensive performance of autoclaved silicate brick. To achieve this aim, the study evaluates the effects of four glass powder fractions and three dosage levels on density, compressive strength, water absorption, thermal conductivity, and frost resistance, identifies the most effective glass fraction and content, and then investigates how varying compaction pressure affects the properties of the composition found to be optimal. In this way, the work addresses both the scientific issue of structure-property relationships in glass-modified silicate systems and the practical issue of selecting technologically justified parameters for recycling glass waste in silicate brick production.

2. Methods

2.1 Materials

The experimental study was carried out based on a conventional quartz-lime system widely used in the production of silicate brick. The initial raw material was a base silicate mixture obtained from a silicate brick manufacturing plant (JSC West Kazakhstan Corporation of Building Materials, Uralsk, Kazakhstan).

According to regulatory documentation [17] for the production of silicate products, the silicate mixture consists of quartz sand, construction lime, and water.

Quartz-feldspar sand from the Melovye Gorki deposit, located 5.5-6 km southeast of Uralsk (Kazakhstan), was used as the siliceous component. The silica (SiO_2) content in the sand was approximately 83.5%, confirming its suitability for use in silicate materials according to [18]. The content of quartz sand in the mixture ranged from 70 to 85%. Ground quicklime of slow slaking type (Grade I) was used as the binding component. The lime was introduced into the mixture in an amount of 8-10 wt.%. The content of amorphous SiO_2 in the glass powder is approximately 70-74%. The glass powder was introduced into the silicate mixture in amounts of 5, 10, and 15 wt.% with partial replacement of quartz sand. Glass powder obtained from container glass waste was used as a modifying additive. The glass waste was preliminarily crushed and then ground in a laboratory ball mill (dry grinding type) of the MSHSP-08 model (JSC Tyazhmash, Syzran, Russia), followed by sieving. The particle size distribution of the glass powder was determined by sieve analysis using a laboratory vibrating sieve SLV-200-11 (VIBROTECHNIK LLC, Saint Petersburg, Russia). Based on the results, the powder was classified into the following particle size fractions: ≤63 μm, 63-140 μm, 140-315 μm, and 315-630 μm. The selected parameters above correspond to standard technological requirements for silicate brick production [19].

2.2 Experimental program

The experimental program was aimed at evaluating the influence of the particle size distribution of glass powder, its content, and compaction pressure on the performance properties of silicate brick. The following parameters were investigated:

- Glass powder content (5, 10, and 15 wt.%);
- Particle size distribution (≤63, 63-140, 140-315, and 315-630 μm);
- Compaction pressure (5-15 MPa).

The optimal particle size fraction and dosage of glass powder were determined based on a comprehensive analysis of the physical, mechanical, and thermophysical properties of the obtained specimens.

2.3 Specimens preparation

The initial components were first subjected to dry manual mixing under laboratory conditions until a homogeneous mixture was obtained. After dry mixing, water was added to achieve a moisture content of 6-8 wt.%, which corresponds to the requirements of semi-dry pressing technology widely used in silicate brick production [20]. Specimen forming was carried out using the semi-dry pressing method with a hydraulic press, PSU-10 (Tehmash LLC, Chelyabinsk, Russia). At the first stage of the experiment, cylindrical specimens with dimensions of 50×50 mm were produced at a compaction pressure of 10 MPa (Figure 1). At this stage, the influence of different particle size fractions and glass powder content was investigated.



Figure 1 – Formed specimens

At the second stage, the compaction pressure was varied in the range of 5-15 MPa for the optimal fraction and content of glass powder to assess the combined effect of particle dispersity and degree of compaction on the material properties. The incorporation of glass components into silicate materials and variations in forming parameters significantly affect the formation of calcium hydrosilicate structures and the physical-mechanical properties of autoclaved products [6].

2.4 Autoclave treatment

The formed specimens were subjected to autoclave treatment under conditions corresponding to the industrial technology of silicate brick production (Figure 2). The treatment was carried out in an autoclave (Chemical Equipment and Industrial Fittings Plant, Kielce, Poland). The autoclaving regime corresponded to the technological mode applied at the silicate brick plant in Uralsk: temperature increase to 174-175 °C over 1.5-2 hours, followed by isothermal holding at 174-175 °C and a saturated steam pressure of approximately 0.8 MPa for 6-8 hours. This was followed by gradual pressure reduction and cooling to atmospheric conditions over 2 hours.



a) Autoclaving b) Cooling

Figure 2 – Treatment of specimens

After completion of the autoclave treatment, the specimens were cooled and conditioned under laboratory conditions until stable temperature and mass values were achieved.

2.5 Physical-mechanical testing

The average density, water absorption, and compressive strength (Figure 3) were determined in accordance with the requirements of the regulatory documents [21], [22] in force in the Republic of Kazakhstan, which govern testing methods for silicate brick and autoclaved silicate products. Compressive strength tests were carried out on cylindrical specimens with dimensions of Ø50×50 mm. The reported strength values were taken as the average results obtained from a series of tests.



Figure 3 – Compression test of specimens

Frost resistance of the specimens was evaluated using a method of repeated freeze-thaw cycles in accordance with national regulatory requirements for silicate products [21]. Freezing of the specimens was performed in a laboratory freezing chamber of the XR series (YUKON, Moscow, Russian Federation).

2.6 Determination of thermal conductivity

The thermal conductivity was determined on specimens that were preliminarily dried to constant mass. Measurements were carried out using an ITP-MG4 device (Stroypribor LLC, Chelyabinsk, Russia) based on the probe method. The tests were performed on prepared specimens using the transient heat flow method. Measurements were conducted at room temperature. For each composition, at least three measurements were performed, and the average value of the thermal conductivity coefficient was calculated based on the obtained results.

3. Results and Discussion

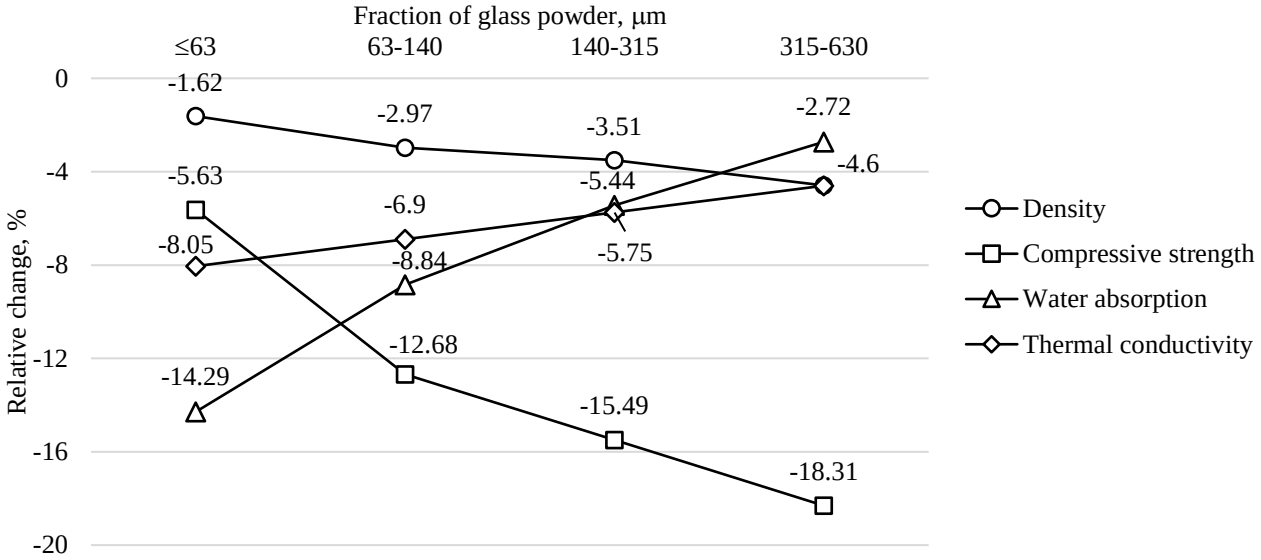
3.1 Effect of particle size distribution and glass powder content

Table 1 and Figure 4 present the physical, mechanical, and thermophysical properties of silicate brick produced in different fractions and contents of finely ground glass powder.

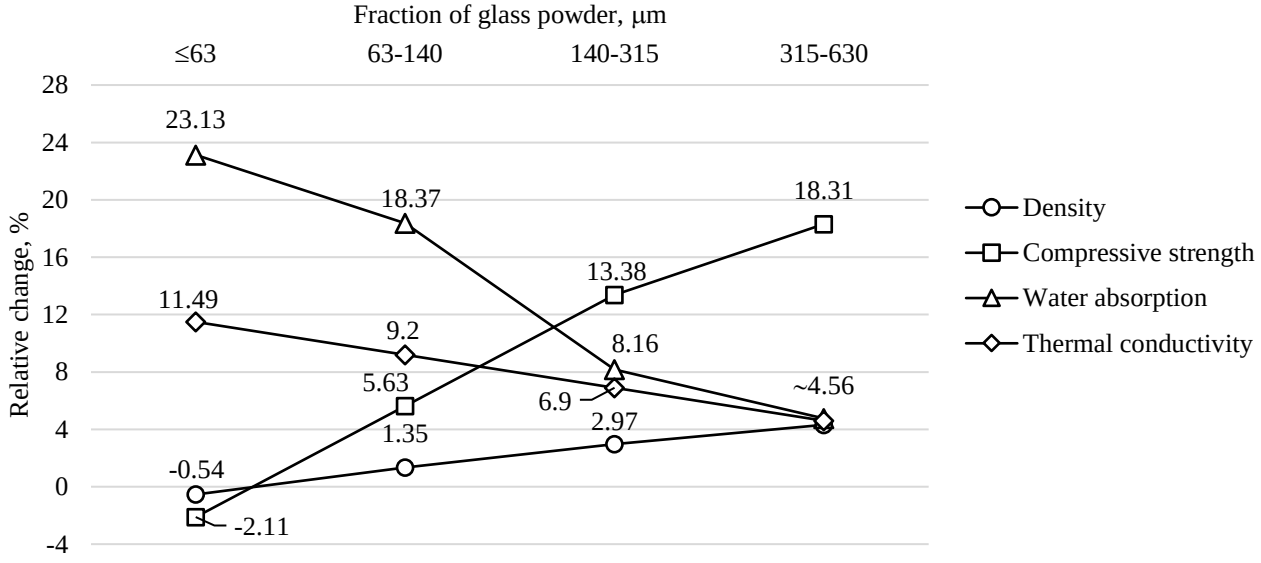
Table 1 – Effect of glass powder particle size distribution and content on the properties of silicate brick (applied compaction pressure of 10 MPa)

Fraction, μm	Glass content, %	Average density, kg/m^3	Average compressive strength, MPa	Average water absorption, %	Average thermal conductivity, W/(m·°C)	Frost resistance, F
	0*	1850	14.2	14.7	0.87	
	5	1820	13.4	12.6	0.80	
≤63	10	1860	14.5	11.3	0.77	
	15	1835	13.8	11.9	0.78	
	5	1795	12.4	13.4	0.81	
63-140	10	1825	13.4	12.0	0.79	
	15	1810	13.0	12.6	0.80	F50
	5	1785	12.0	13.9	0.82	
140-315	10	1795	12.3	13.5	0.81	
	15	1780	12.1	13.8	0.82	
	5	1765	11.6	14.3	0.83	
315-630	10	1770	11.6	14.0	0.83	
	15	1760	11.4	14.5	0.84	

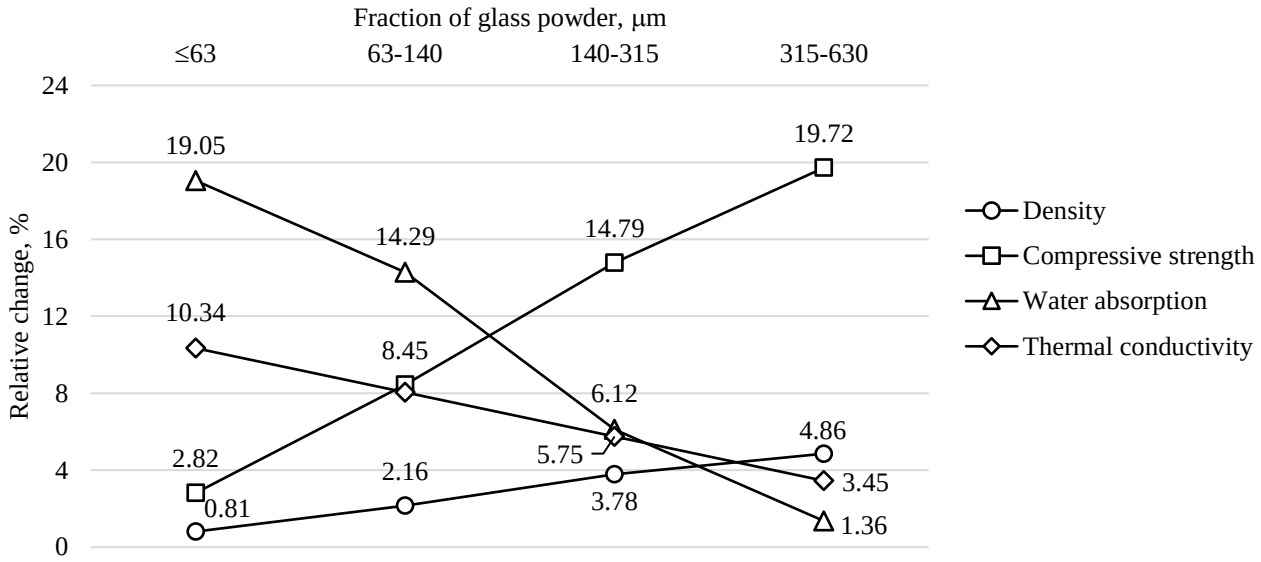
* Reference specimen.



a) Glass content of 5 %



b) Glass content of 10%



c) Glass content of 15%

Figure 4 – Relative change in the properties of silicate brick compared to the reference specimen

Table 1 and Figure 4 jointly show that the effect of glass powder on silicate brick is controlled by both particle size distribution and content, with the finest fraction giving the best overall results. The clearest positive effect is observed for the ≤63 μm fraction at 10% addition, where the average density increases from 1850 to 1860 kg/m^3, compressive strength from 14.2 to 14.5 MPa, while water absorption decreases from 14.7 to 11.3% and thermal conductivity from 0.87 to 0.77 W/(m·°C). Figure 4 confirms this as the most favorable combination, corresponding to +0.54% in density, +2.11% in compressive strength, −23.13% in water absorption, and −11.49% in thermal conductivity relative to the reference specimen. A similar positive effect of glass incorporation in autoclaved sand-lime systems was reported by [2] and [3], who showed that glass-containing autoclaved materials can exhibit improved strength and reduced water uptake due to favorable hydrothermal structure formation.

At the same time, Table 1 and Figure 4 show that increasing the content of the same fine fraction from 10% to 15% weakens the positive effect: density falls to 1835 kg/m^3, compressive strength to 13.8 MPa, and the relative change in strength becomes negative (−2.82%). Although water absorption (11.9%) and thermal conductivity (0.78 W/(m·°C)) remain better than in the reference specimen, the overall performance is lower than at 10%, suggesting that excessive glass powder reduces structural uniformity. The presence of an optimum additive content rather than a monotonic improvement is consistent with the results of [9], who also found that moderate waste addition in autoclaved brick was more beneficial than higher dosages.

For the 63-140 μm fraction, the values in Table 1 remain less favorable than for the finest powder, although some improvement is still observed. At 10% glass content, density reaches 1825 kg/m^3, compressive strength 13.4 MPa, water absorption 12.0%, and thermal conductivity 0.79 W/(m·°C). Figure 4 shows that these changes are moderate: density is still 1.35% below the reference and compressive strength 5.63% lower, even though water absorption and thermal conductivity decrease by 18.37% and 9.20%, respectively. This suggests that with increasing particle size, glass powder remains beneficial mainly for physical and thermophysical properties, while its strengthening effect becomes weaker. This weaker strengthening effect with increasing glass particle size agrees with the general trend reported by [12], who showed that waste-glass particle size strongly controls density, strength, and absorption behavior in brick materials.

For the 140-315 μm fraction, Table 1 shows only limited variation with glass content: density remains within 1780-1795 kg/m^3, compressive strength within 12.0-12.3 MPa, water absorption within 13.5-13.9%, and thermal conductivity within 0.81-0.82 W/(m·°C). Figure 4 likewise shows that all relative changes remain modest and compressive strength stays below the

reference level at all dosages. Thus, this fraction has only a weak modifying effect. The limited modification effect observed here is also comparable to the pore-structure study of [7], where the performance of autoclaved glass-modified materials was closely linked to how effectively the additive altered the porous structure.

The 315-630 μm fraction gives the least favorable results. According to Table 1, density decreases to 1760-1770 kg/m^3, compressive strength to 11.4-11.6 MPa, while water absorption rises to 14.0-14.5% and thermal conductivity to 0.83-0.84 W/(m·°C). Figure 4 confirms the negative trend, especially for compressive strength, which decreases by 18.31-19.72% relative to the reference specimen. Thus, the unfavorable behavior of the coarsest fraction further supports the conclusion that glass in autoclaved silicate systems is most effective in a sufficiently fine state, as also indicated in studies of glass-based autoclaved materials [2], [3].

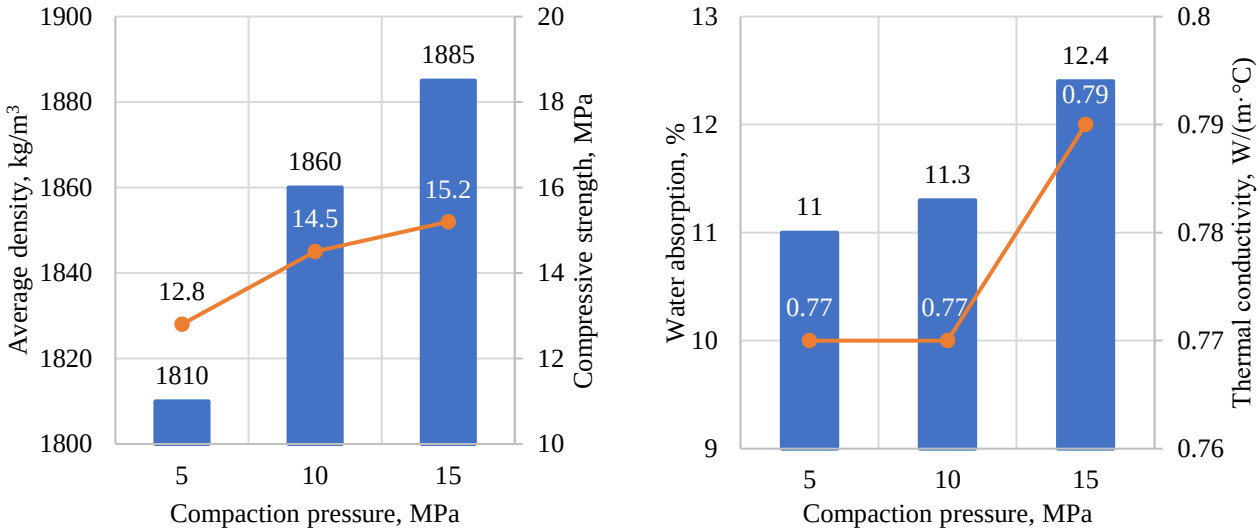
Overall, Table 1 provides the absolute values, while Figure 4 clearly highlights the relative trends: the beneficial effect of glass powder is strongest for the finest fraction and reaches an optimum at 10% content. As particle size increases, the improvement becomes progressively weaker, and for the coarsest fraction, the effect becomes unfavorable.

3.2 Frost resistance

Despite differences in physical and mechanical properties, all investigated specimens demonstrated frost resistance at the level of F50.

3.3 Effect of compaction pressure

Figure 5 illustrates the effect of compaction pressure on the properties of silicate brick produced using the optimal glass powder fraction (≤63 μm) at a content of 10%.



a) Physical-mechanical properties b) Hydro-thermal properties

Figure 5 – Effect of applied compaction pressure on the properties of silicate brick

The results show that increasing the compaction pressure from 5 to 15 MPa leads to an increase in the average density of the material from 1810 to 1885 kg/m^3, and in compressive strength from 12.8 to 15.2 MPa. An increase in compaction pressure promotes the reduction of intergranular voids and results in denser particle packing, leading to the formation of a more compact silicate matrix. At the same time, water absorption decreases from 12.4 to 11.0%, indicating a reduction in the volume of open pores within the material structure. The thermal conductivity coefficient varies within the range of 0.77-0.79 W/(m·°C), which indicates a minor influence of compaction pressure on the thermophysical properties of the material. The observed increase in density and compressive strength, together with lower water absorption at higher compaction pressure, is consistent with the behavior of other autoclaved lime-based bricks, where

denser packing and more favorable structure formation improved the main performance characteristics [1].

3.5. Limitations of the study and prospects for future research

Despite the obtained results, certain limitations of the present study should be noted. The work considered a limited range of glass powder particle size distributions and compaction pressure. In future research, it is advisable to expand the range of dispersity parameters investigated, as well as to conduct a more detailed microstructural analysis using SEM and XRD methods in order to achieve a deeper understanding of the structure formation mechanisms in modified silicate systems.

4. Conclusion

This study established that the performance of autoclaved silicate brick modified with glass powder depends on the combined influence of particle size distribution, additive content, and compaction pressure. Among the investigated fractions, the finest glass powder (≤63 μm) showed the highest modification efficiency. At a content of 10 wt.% and a compaction pressure of 10 MPa, the material exhibited the most balanced set of properties, reaching an average density of 1860 kg/m^3, compressive strength of 14.5 MPa, water absorption of 11.3%, and thermal conductivity of 0.77 W/(m·°C). These results indicate that finely ground glass powder contributes to the densification of the silicate matrix and improvement of both mechanical and thermophysical performance.

An increase in glass powder content from 10 to 15 wt.% did not provide further overall improvement, which indicates the presence of an optimum dosage. In addition, as the particle size of the glass powder increased from ≤63 μm to coarser fractions, the positive effect became progressively weaker, and for the 315-630 μm fraction, the modification efficiency was unfavorable relative to the reference composition. This confirms that the reactivity and modifying effect of glass powder in silicate systems are strongly controlled by dispersity.

The variation of compaction pressure for the optimal composition showed that increasing pressure from 5 to 15 MPa led to an increase in density from 1810 to 1885 kg/m^3 and compressive strength from 12.8 to 15.2 MPa, while water absorption decreased from 12.4 to 11.0%. At the same time, thermal conductivity remained within a narrow range of 0.77-0.79 W/(m·°C), indicating that compaction pressure had a stronger effect on physical-mechanical properties than on thermophysical behavior.

For all investigated compositions, frost resistance remained at the level of F50, which confirms that the incorporation of glass powder within the studied range did not reduce the frost durability of the silicate brick. Overall, the use of glass powder with a particle size ≤63 μm at a content of 10 wt.% can be regarded as the most effective solution among the studied variants, and the results confirm the practical potential of recycling glass waste in the production of silicate brick with improved performance characteristics.

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Bolatbek Sakhiev – data collection, interpretation, drafting.
Sabit Zharylgapov – methodology, editing.
Ainur Montayeva – testing, modeling, visualization.

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