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Effects of Waste Glass and Expanded Clay Dust on Physical, Mechanical, and Thermal Properties of Autoclaved Silicate Composites

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ABSTRACT

Incorporating mineral by-products into autoclaved silicate products can reduce virgin-material consumption and alter their thermal and mechanical performance. This study evaluated factory-derived sand-lime silicate composites modified with ground waste glass and expanded clay dust. An unmodified factory silicate mass served as the reference. It wascompared descriptively with three modified formulations containing silicate mass, waste glass, and expanded clay dust at mass ratios of 87/3/10, 75/5/20, and 60/10/30. Cylindrical specimens (50 mm in diameter and 50 mm in height) were produced by semi-dry pressing at 12 MPa and autoclaved under factory conditions. Bulk density, compressive strength, water absorption, and thermal conductivity were determined according to the standards cited by the authors. Optical microscopy, scanning electron microscopy (SEM), and energy-dispersive X-ray spectroscopy (EDS) were employed for descriptive microstructural characterization. Across the investigated series, bulk density decreased from 1.80 g/cm^3 for the unmodified silicate mass to 1.69 g/cm^3 for the 60/10/30 formulation, corresponding to a 6.1% reduction. Thermal conductivity decreased from 0.87 to 0.56 W/(m·K), representing a 35.6% reduction, while compressive strength decreased from 47.8 to 30.3 MPa and water absorption increased from 15.2% to 20.2%. SEM observations revealed glass-rich particles embedded within the autoclaved matrix, while EDS indicated a Ca-Si-Al-rich elemental composition; however, these techniques did not establish the presence of specific crystalline hydration phases. Because replicate numbers,dispersion measures, and inferential statistical analyses were not reported, the results should be interpreted as descriptive trends rather than statistically validated differences. The combined additives reduced density and thermal conductivity but adversely affected compressive strength and water absorption. Among the modified formulations, the 87/3/10 mixture exhibited the most conservative balance of properties. Further investigation of durability, frost resistance, phase assemblage, statistical reproducibility, and life-cycle impacts is required before conclusions regarding standards compliance, environmental benefits, or industrial-scale applicability can be drawn.

Keywords: *Autoclaved silicate composite, Expanded clay dust, Thermal conductivity, Waste glass, Water absorption, Compressive strength*

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INTRODUCTION

Kazakhstan's construction sector is being shaped by national environmental-policy priorities, climate commitments, circular-economy objectives, and expectations for responsible infrastructure investment (Hor *et al*., 2022; Karaca & Tleuken, 2024; Le *et al*., 2025; Organisation for Economic Co-operation and Development [OECD], 2025; Turgel *et al*., 2025). Within this context, diverting mineral by-products from disposal may reduce demand for virgin resources (Alhmoud *et al*., 2025). However, such benefits cannot be assumed from waste incorporation alone; they depend on processing requirements, product service life, emissions, transport, and end-of-life performance.

For masonry products, density, compressive strength, water absorption, and thermal conductivity are interdependent performance variables. Studies of porous clay bricks show that lower density and thermal conductivity can be accompanied by lower strength or higher water uptake (Bilgil *et al*., 2024). Building mass also affects structural and seismic demand, while masonry response depends on constituent and assembly properties (Hysenlliu *et al*., 2020; Korswagen *et al*., 2020). Thermal conductivity is additionally governed by mineralogy, porosity, density, moisture, and temperature (Kotrbova *et al*., 2025). Consequently, a lower-density silicate product is useful only if its mechanical and moisture-related performance remains appropriate for the intended exposure and structural function.

Alternative mineral additions are widely investigated as partial substitutes or functional modifiers in lower-emission cementitious materials (Kapeluszna *et al*., 2021). Waste-glass research has examined aggregate replacement, fine-powder reactivity, and durability in concrete and soil-cement systems (Lakhouit, 2025; Sivasuriyan & Koda, 2025). Clay and clayderived materials may also contribute aluminosilicate phases and filler effects in construction binders (Singh, 2022). Transfer of these findings to autoclaved calcium-silicate products requires caution because hydrothermal curing, lime-silica reactions, particle-size distributions, and pore structures differ from those of ordinary Portland cement concrete or fired clay products.

Evidence relevant to brick manufacture indicates that waste glass can alter compaction, sintering, strength, porosity, and thermal behavior. Reported applications include glass-powder stabilization of Siwalik clay (Ashiq *et al*., 2022),pervious concrete containing crushed glass (Sathiparan & Subramaniam, 2024); kenaf-fiber lateritic bricks (Akinwande *et al*., 2024), fired clay bricks produced from contaminated glass dust (Xin *et al*., 2023), predictive modeling of glass-containing bricks (Khokhar *et al*., 2023), broader reviews of by-products in fired and unfired bricks (Singh *et al*., 2023), and fired earth bricks containing plant fiber and glass powder (Bali *et al*., 2024). Collectively, these studies show that performance depends strongly on matrix type, glass fraction, particle size, curing or firing regime, and the presence of other additives.

The broader literature on cementitious materials reinforces this formulation dependence. Recycled-glass concrete studies have combined microstructural characterization with predictive modeling (Sobuz *et al*., 2025). At the same time, glass micro-powder has been investigated in solidified soils (Lai & Chen, 2024),and particle-size effects have been evaluated in soil improvement (Akoguz, 2025). Surface treatment can modify the behavior of recycled glass in concrete (Al-Awabdeh *et al*., 2022), and machine-learning approaches have been used to predict the strength of mixtures containing waste glass (Wang *et al*., 2024). Other applications include semi-flexible pavement grouts (Al-Nawasir *et al*., 2024), ultra-high-performance concretes containing glass and limestone powders (Abellan-Garcia *et al*., 2024) or basalt fiber and glass powder (Salahaddin *et al*., 2024), recycled-glass-fiber/agricultural-ash systems (Mkilima *et al*., 2024), and nano-sized waste-glass powders (Odaa *et al*., 2023).

These studies demonstrate the versatility of glass-derived constituents but do not establish a single optimal dosage for autoclaved silicate products.

Waste glass has also been incorporated into polymer-bound artificial stone (Barreto *et al*., 2023), insulation materials produced with spent battery constituents (Cozzarini *et al*., 2023), high-porosity alkali-activated binders (Maldonado-Alameda *et al*., 2023), mechanically or chemically activated mortars (Sun *et al*., 2022), high-volume glass-powder concrete (Tahwia *et al*., 2022), and cement-based materials in which glass replaces aggregate (Harrison *et al*., 2020). Research on modification efficiency emphasizes the importance of processing and replacement level (Gao *et al*., 2020), and polymer-composite work similarly shows that fine glass particles may improve selected properties at moderate contents but agglomerate at higher contents (Sheikh *et al*., 2025). These findings support controlled optimization rather than assuming that increasing glass content will produce monotonic improvement.

Expanded clay dust may provide a complementary function because of its low bulk density and aluminosilicate composition. Earlier studies describe the use of expanded-clay-production waste in construction materials (Khlystov *et al*., 2014) and report pozzolanic behavior when the dust is sufficiently reactive (Rakhimov *et al*., 2013). Solid-waste ceramsite has been investigated in lightweight high-strength concrete (Tang *et al*., 2024), while expanded clay aggregate combined with silica fume has been used in lightweight concrete (Ahmad *et al*., 2019) and structural lightweight self-compacting concrete (Nepomuceno *et al*., 2018). Nevertheless, aggregate-scale expanded clay and kiln-captured dust are not equivalent materials; their particle size, firing history, surface area, absorption, and reactivity must be characterized separately.

Related waste-valorization studies include clay-brick dust in durable mortar (Li *et al*., 2020), extensive waste-glass use in one-part alkali-activated materials (Samarakoon *et al*., 2021), upcycling of glass wool and spodumene tailings in building ceramics (Lemougna *et al*., 2024), sawdust in concrete and brick applications (Priya *et al*., 2025), mixed mineral wastes in geopolymer composites (Uysal *et al*., 2022), tea waste in solid bricks (Crespo-Lopez *et al*., 2024), multi-waste porous insulating bricks (Pandey *et al*., 2024), and concrete bricks containing pond ash and recycled glass sand (Patrisia *et al*., 2024). These studies demonstrate multiple routes to lower-density or waste-integrated products, but the resulting thermal, strength, moisture, and durability responses remain system-specific.

Evidence from electric-arc-furnace dust binders (Fares *et al*., 2016), quarry-dust concrete blocks (Febin *et al*., 2019), broader reviews of building materials and bricks (Jonnala *et al*., 2024), fiber-modified recycled bricks (Tang *et al*., 2022), waste-glass mortars (Bameri *et al*., 2025), and bioclimatic building design (Xhexhi & Aliaj, 2024) further indicates that material-level improvements must ultimately be evaluated against component-scale and whole-building requirements. Accordingly, environmental claims should be based on quantified life-cycle comparisons rather than on waste diversion alone (Oud *et al*., 2025).

Despite the extensive literature on waste glass and lightweight mineral constituents, evidence on their combined use in autoclaved sand-lime silicate composites remains limited, particularly for industrial by-products generated in western Kazakhstan. The principal knowledge gap concerns whether simultaneous addition of ground glass and expanded clay dust can reduce density and thermal conductivity while retaining acceptable strength and moisture behavior.

This study therefore evaluated three waste-modified silicate formulations against an unmodified factory silicate mass. The objectives were to characterize the source materials, describe changes in bulk density, compressive strength, water absorption, and thermal conductivity, and examine the autoclaved microstructure using optical microscopy, SEM, and EDS.

MATERIALS AND METHODS

The base material was a preformulated sand-lime silicate mass supplied by Zapadno-Kazakhstanskaia korporatsiia stroitelnykh materialov, LLP, a silicate-brick manufacturer in Uralsk, Kazakhstan. The supplied manuscript did not report batch identifiers, sampling dates, or the exact lime-to-sand ratio of the factory mass.

The factory process comprised sand extraction and sieving; limestone calcination; co-grinding of lime with part of the sand; blending with unmilled sand and water; slaking; secondary mixing and moisture adjustment; pressing; and autoclaving in saturated steam. The reported production pressure and maximum temperature were 0.8 MPa and approximately 174.5 °C, respectively.

The routine factory curing schedule was reported as 1.5 h heating to 174 °C, 8 h at the maximum temperature, and 2 h cooling to 100 °C with depressurization. The experimental specimens were subjected to a different cycle: 2 h heating, 6 h holding, and 2 h cooling, as described below; this difference should be considered when comparing laboratory specimens with factory products.

Quartz sand was obtained from the Melovyye Gorki deposit, approximately 5.5-6 km southeast of Uralsk. **Table 1** summarizes its reported oxide composition and physical properties. The manuscript did not identify the analytical method, number of determinations, or measurement uncertainty for these values.

Table 1. Reported chemical composition and physical properties of quartz sand from the Melovyye Gorki deposit.

Parameter	Value
Chemical composition (%)	
Silicon dioxide (SiO_2)	83.5
Calcium oxide (CaO)	2.5
Magnesium oxide (MgO)	2.9
Aluminum oxide (Al_2O_3)	4.3
Iron(III) oxide (Fe_2O_3)	1.3
Alkali metal oxides (R_2O)	1.6
Sulfur trioxide (SO_3)	2.7
Loss on ignition (LOI)	1.2
Total	**100**
Physical properties	
Fineness modulus	1.49
Bulk density (kg/m^3)	1485
True density (g/cm^3)	2.63
Void content (%)	44
Contamination (%)	0.9

The lime was described as powdered grade 1, slow-slaking quicklime with at least 90% active CaO + MgO and conforming to GOST 9179-2018. Confirm the current applicability and full bibliographic details of this standard for the target journal.

Ground waste glass was obtained from STEKLOSERVIS, LLP, a double-glazed window manufacturer in the West Kazakhstan region.The manufacturer reportedly generates approximately 2,000 tonnes of glass waste annually. The glass was used as a partial replacement within the factory silicate mass; glass color, pre-cleaning, grinding equipment, mineralogical composition, amorphous content, and moisture content were not reported.

Expanded clay dust was collected from STROIKOMBINAT, LLP, an expanded-clay-gravel producer in Uralsk. The plant reportedly has an annual production capacity exceeding 200,000 m^3.

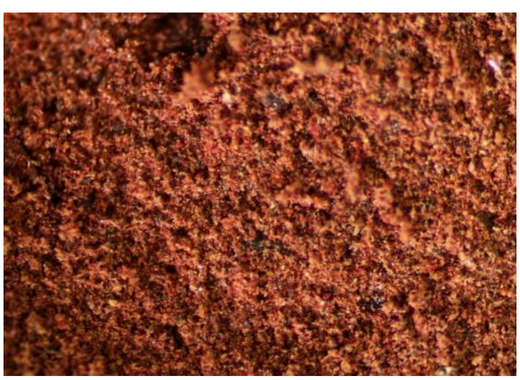
The dust is generated during high-temperature firing of montmorillonitic clay, entrained from the rotary kiln, and captured by filtration equipment.The plant reportedly generates more than 500 m^3 of dust annually and disposesof most of it to landfill. The source enterprises provided these production and disposal quantities, and the supplied manuscript did not independently verify them.

The reported oxide composition of the expanded clay dust on a dry basis was:

SiO2 = 59.07%, TiO2 = 0.97%, Al2O3 = 17.82%, Fe2O3 = 9.64%, MnO = 0.44%, CaO = 1.78%, MgO = 2.97%, Na2O = 0.85%, K2O = 2.23%, P2O5 = 0.25%, SO3 = 0.91%, and loss on ignition = 3.07%. The analytical procedure, number of replicates, and uncertainty were not reported.

The reported loose bulk density of the expanded clay dust ranged from 600 to 800 kg/m^3.

Powder fineness was measured with a PSKh-17 air-permeability instrument using a Kozeny-Carman-type procedure. The source manuscript expressed the specific surface area as 2,800-3,000 g/cm^2; because specific surface area is conventionally reported in cm^2/g, the value is presented here as a probable unit correction that requires author confirmation. Optical images were acquired with a Levenhuk 320 Series microscope **(Figure 1)**. SEM and EDS analyses were performed using a Hitachi TM4000 Plus instrument **(Figure 2; Table 2)**. Accelerating voltage, working distance, coating procedure, number of fields, and EDS acquisition conditions were not fully reported.



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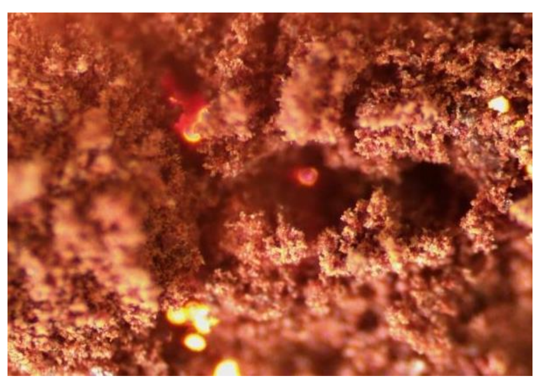

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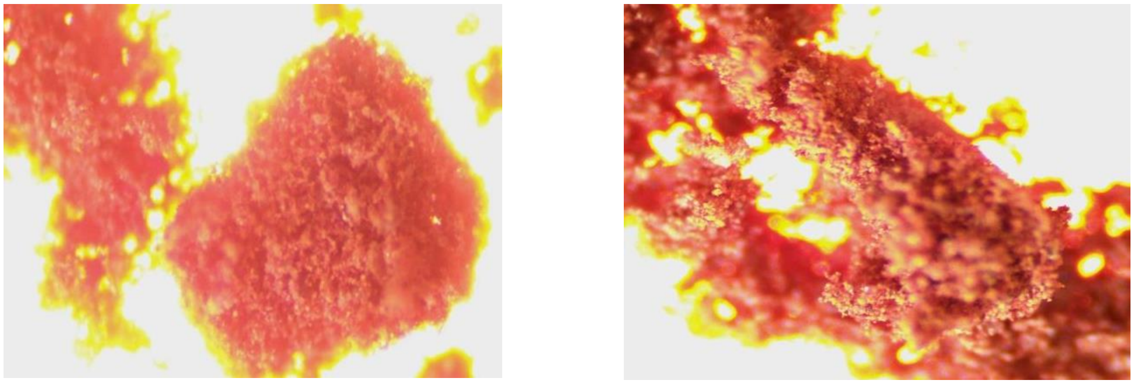
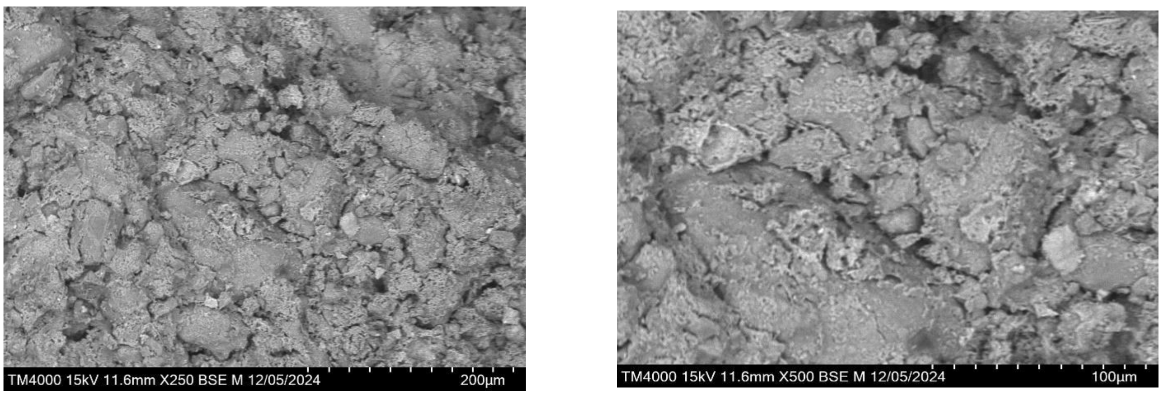


c) d)

Figure 1. Optical micrographs of expanded clay dust from STROIKOMBINAT, LLP (x100): (a, b) particle surfaces; (c, d) dispersed particles.



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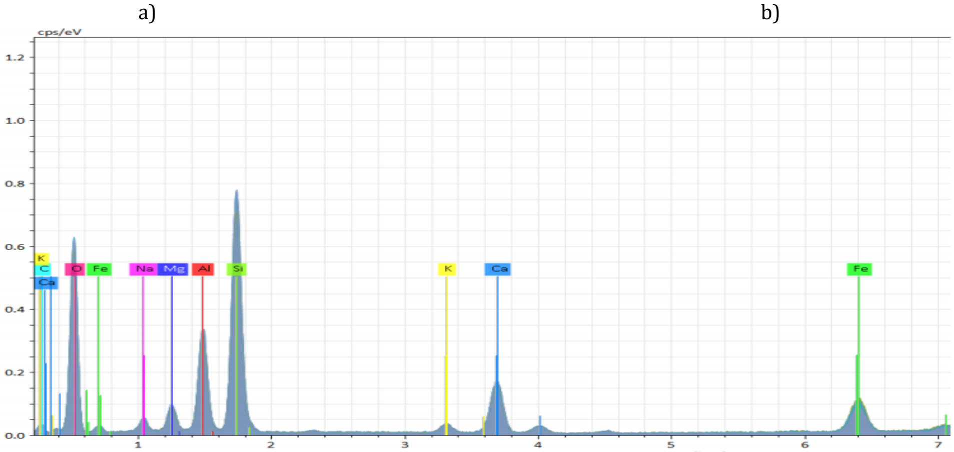


c)

Figure 2. SEM and EDS characterization of expanded clay dust: (a) microstructure at x250; (b) microstructure at x500; (c) representative EDS spectrum.

Table 2. Normalized elemental mass fractions of expanded clay dust determined by SEM-EDS (%).

Spectrum	C	N	O	Fe	Ca	K	Si	Al	Mg	Na
2 3	0.00	7.81	41.20	6.37	9.51	1.35	24.38	7.04	1.46	0.88
2 1			42.71	7.28	11.09	1.59	27.02	7.64	1.63	1.04
2 2			50.17	5.75	8.32	1.27	23.22	7.95	2.01	1.31
Mean	0.00	7.81	44.70	6.47	9.64	1.40	24.87	7.54	1.70	1.08
Sigma	0.00	0.00	4.80	0.77	1.39	0.17	1.95	0.47	0.28	0.22
SigmaMean	0.00	0.00	2.77	0.45	0.80	0.10	1.12	0.27	0.16	0.12

The EDS results indicate that oxygen, silicon, calcium, aluminum, and iron were the principal detected elements. Together with the bulk oxide analysis, these results are consistent with an aluminosilicate-rich material. The optical andSEM images show irregular, porous particles. These observations support its potential role as a low-density filler, but they do not by themselves demonstrate pozzolanic activity or predict strength development.

The preliminary characterization justified testing expanded clay dust together with ground waste glass as a combined density-reducing and silica-bearing addition. No independent reactivity test, phase analysis, or isothermal-calorimetry measurement was reported before formulation.

RESULTS AND DISCUSSION

Four compositions were evaluated descriptively: the unmodified factory silicate mass and three modified mixtures. The modified mixtures contained silicate mass/ground waste glass/expanded clay dust at 87/3/10 (Composition 1), 75/5/20 (Composition 2), and 60/10/30 (Composition 3) mass percentages.

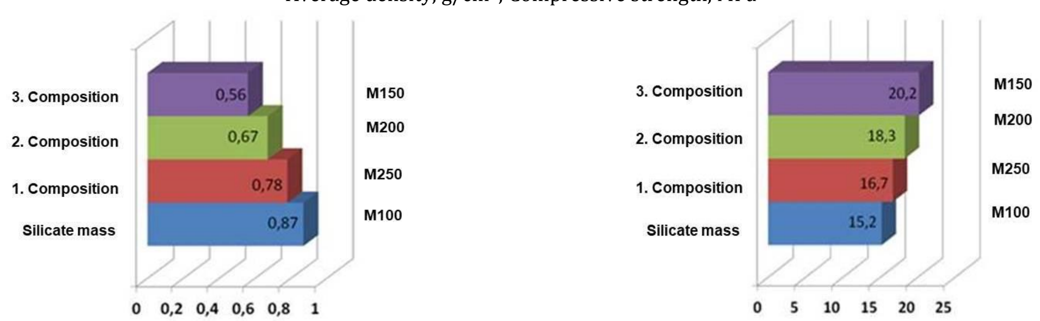
The ground glass and expanded clay fractions were reported to range from 0.14 to 1.25 mm. The materials were weighed on electronic balances and blended as three-component mixtures. The authors did not report mixing time, mixer type, addition sequence, particle-size distribution within this range, or batch replication.

Cylindrical specimens measuring 50 mm in diameter and 50 mm in height were formed by semi-dry pressing at 12 MPa using a PSU-12 hydraulic press. The forming water content was approximately 10% of dry-solids mass. Specimens were autoclaved under factory conditions using a 2 h heating stage, 6 h hold, and 2 h cooling stage. The number of specimens per formulation, specimen randomization, and achieved autoclave temperature-pressure profile were not reported.

After cooling, the authors recorded dimensions and mass and reported testing of compressive strength, water absorption, frost resistance, and thermal conductivity with reference to GOST 8462-85 and GOST 10180-90. The exact apparatus, conditioning protocol, loading rate, thermal-conductivity method, test temperature, number of replicates, and frost-resistance results were not supplied. Consequently, the following comparisons are descriptive and cannot establish statistical significance or formal standards compliance.

Figure 3 presents the reported physical and mechanical values.

Average density, g/cm³; Compressive strength, MPa



Thermal conductivity, W/(m·K) Water absorption,%

Figure 3. Reported properties of the unmodified silicate mass and three modified compositions. Composition 1 = 87/3/10, Composition 2 = 75/5/20, and Composition 3 = 60/10/30 silicate mass/ground waste glass/expanded clay dust by mass. Error bars were not provided.

The unmodified silicate mass had a reported bulk density of 1.80 g/cm^3, compressive strength of 47.8 MPa, thermal conductivity of 0.87 W/(m·K), and water absorption of 15.2%. Corresponding values for Compositions 1, 2, and 3 were 1.78, 1.74, and 1.69 g/cm^3; 45.7, 38.6, and 30.3 MPa; 0.78, 0.67, and 0.56 W/(m·K); and 16.7%, 18.3%, and 20.2%, respectively. Relative to the control, Composition 3 therefore showed a 6.1% reduction in density and a 35.6% reduction in thermal conductivity, accompanied by a 36.6% reduction in compressive strength and a 32.9% increase in water absorption.

The results show a monotonic trade-off across the tested formulation series: increasing the combined additive fraction coincided with lower density and thermal conductivity but also lower compressive strength and higher water absorption. Composition 1 produced the smallest departure from the control (density -1.1%, thermal conductivity -10.3%, compressive strength -4.4%, and water absorption +9.9%). Because the glass and expanded-clay contents changed simultaneously, their individual effects and any interaction cannot be separated.

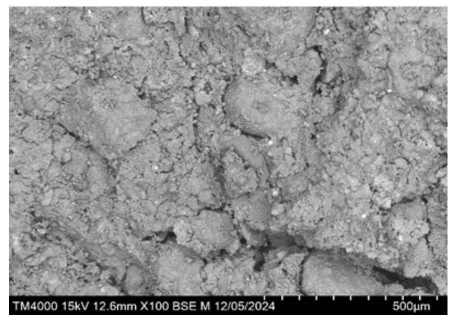
Figure 4 and **Table 3** show SEM images and EDS data for the autoclaved composite. The EDS measurements were dominated by oxygen, silicon, calcium, aluminum, and iron, consistent with the sand-lime matrix and aluminosilicate addition.

Table 3. Normalized elemental mass fractions of the autoclaved composite determined by SEM-EDS (%).

Spectrum	C	O	Fe	Mn	Ca	K	S	Si	Al	Mg	Na
4 1	0.00	43.05	5.64		16.77	1.05	1.57	19.99	8.10	2.77	1.07
4 2		39.52	6.81	1.70	11.66	0.82	0.56	26.63	8.78	2.42	1.10
4 3	1.45	46.82	2.75		12.38	3.15	1.88	22.60	6.97	1.16	0.83
Mean	0.73	43.13	5.07	1.70	13.60	1.67	1.34	23.07	7.95	2.12	1.00
Sigma	1.03	3.65	2.09	0.00	2.77	1.29	0.69	3.35	0.91	0.84	0.15
SigmaMean	0.59	2.11	1.21	0.00	1.60	0.74	0.40	1.93	0.53	0.49	0.09

Optical and SEM images show glass-rich particles embedded in and coated by the surrounding matrix. The images are consistent with physical integration of the additives after autoclaving. Still, morphology and point EDS spectra cannot establish uniform dispersion throughout the bulk specimen, interfacial bond strength, or the identity and quantity of calcium-silicate-hydrate or tobermorite phases. These questions require replicated imaging together with phase-sensitive methods such as X-ray diffraction and, where appropriate, thermal or spectroscopic analysis.

a)



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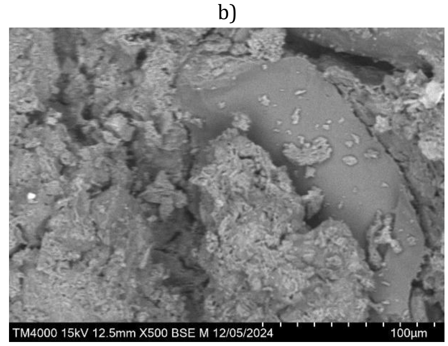

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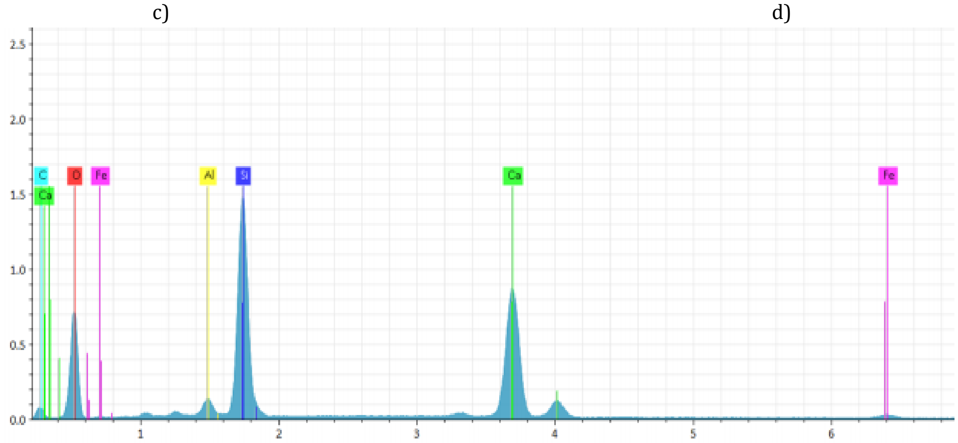

e)

Figure 4. Microstructural characterization of an autoclaved glass/expanded-clay-dust silicate composite: (a) optical macrostructure; (b-d) SEM images at x100, x250, and x500; (e) representative EDS spectrum.

The observed performance pattern is consistent with a combined filler-porosity mechanism. Expanded clay dust has lower bulk density than the factory silicate mass and can increase pore volume, thereby reducing solid-phase heat-transfer pathways. Ground glass may contribute particle-packing or reactive-silica effects,depending on its fineness and amorphous fraction. In the present study, however, glass content and expanded-clay-dust content were not varied independently, total porosity and pore-size distribution were not measured, and no phase analysis was performed. Any mechanistic interpretation must therefore remain provisional.

The increase in water absorption is important when assessing potential applications. A more connected capillary pore system can improve thermal insulation while increasing moisture ingress, which may alter thermal performance in service and heighten susceptibility to freeze-thaw damage. The manuscript states that frost resistance was tested but provides no values; durability equivalence to commercial silicate brick therefore cannot be assessed.

From a resource-efficiency perspective, the formulations demonstrate a technically plausible route for incorporating locally generated mineral by-products.However, they do not yet demonstrate a lower life-cycle environmental impact. The study did not quantify energy use for grinding, transport, or autoclaving; reject rates; service life; moisture-related performance; or end-of-life management. The pale-brown color attributed to expanded clay dust may be aesthetically useful, but the ability to replace synthetic pigment was not tested quantitatively.

The absence of reported replicate numbers, variability estimates, inferential statistics, independent factor variation, raw-data tables, complete test protocols, and validated phase identification limits the study. The source manuscript also does not provide frost-resistance results, long-term durability data, leaching or hazardous-substance assessment, or a life-cycle inventory. The labels M100-M250 shown in **Figure 3** are not reconciled with the reported MPa values and should be checked against the original test sheets and applicable product standard. Company-reported waste volumes and the probable specific-surface-area unit correction also require author confirmation.

CONCLUSION

Within the reported experimental series, increasing the combined proportion of ground waste glass and expanded clay dust was associated with lower bulk density and thermal conductivity, lower compressive strength, and higher water absorption. Relative to the unmodified silicate mass, the 60/10/30 formulation reduced bulk density by 6.1% and thermal conductivity by 35.6%, while compressive strength decreased by 36.6% and water absorption increased by 32.9%. The 87/3/10 formulation provided a smaller reduction in thermal conductivity but maintained the overall performance closest to that of the unmodified material among the modified formulations. Microscopy provided evidence of the incorporation of additive particles within the autoclaved matrix, while EDS indicated a Ca-Si-Al-rich elemental composition. However, these observations do not establish the presence of specific crystalline hydration phases or distinguish the individual contributions of waste glass and expanded clay dust. Given the descriptive nature of the reported results, further replicated and factorial investigations are required, including characterization of pore structure and phase assemblage, moisture-dependent thermal behavior, frost and chemical durability, leaching, and life-cycle impacts. Such evidence is necessary before making robust claims regarding industrial applicability, environmental performance, or long-term durability.

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ETHICS STATEMENT: None

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