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Effects of Waste Glass as an Additive on the Physical and Mechanical Properties of Building Bricks Made from Low-Grade Clay Material from West Kazakhstan

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Abstract: This study aims to explore the utilization of waste glass (cullet) and bentonite clay as additives to improve the physical and mechanical properties of building bricks made from low-grade clay materials of West Kazakhstan. The research addresses both environmental challenges related to glass waste recycling and the efficient use of locally available raw materials in ceramic production. During the research, clay samples from the Rubezhinsk deposit and bentonite clay from the Pogodayev field were used. Two types of three-component mixtures were prepared: (1) loess clay-bentonite powder-waste glass, and (2) loess clay-bentonite suspension-waste glass. Additives were varied between 5%–25% for bentonite and 5%–15% for waste glass. Standard procedures, including semi-dry pressing, thermal analysis, and scanning electron microscopy, were employed to evaluate the chemical composition, microstructure, plasticity, drying sensitivity, compressive and flexural strength, frost resistance, and water absorption. The introduction of bentonite and cullet significantly enhanced the performance of the ceramic mass. Due to its colloidal properties, the bentonite suspension led to better compaction, lower porosity, and higher compressive strength (up to 13.2 MPa) compared to powder-based mixtures. Microstructural analysis revealed the formation of albite and anorthite crystalline phases that acted as reinforcing agents. The modified mixtures showed reduced drying sensitivity, improved frost resistance, and lower water absorption. The optimized composition of loess clay with bentonite suspension and cullet is a promising solution for producing high-quality, eco-friendly ceramic bricks. The use of waste glass enhances the bricks’ technical properties and contributes to sustainable waste management practices in Kazakhstan.

Keywords: Bentonite, Ceramic brick, Cullet, Semi-dry pressing, Strength

1 Introduction

Today, waste utilization is one of the most complex and important tasks in the waste management system. In the framework of waste reduction, Kazakhstan seeks to use landfill disposal less and increasingly apply alternative waste disposal methods, such as recycling.

Kazakhstan currently generates more than 369 thousand t of waste glass annually. The recycling of waste glass is practically non-existent. At the state level, legislative reforms are adopted to address waste recycling, and landfills for

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sorting and collecting municipal solid waste are created. However, these measures are not enough. Comprehensive systematic work needs to be carried out to develop recycling solutions with their subsequent application in various production sectors.

European experience shows positive dynamics by the example of European Economic Community (EEC) countries, and in 2022, the level of glass recycling in Europe reached 80.2% [1]. Globally, glass recycling is still a challenge, because glass is intended for single use, for example, in beverage bottles, which is one of the main applications of glass. Glass recycling requires logistical solutions and is expensive due to the high costs of operating furnaces, which lowers motivation for recycling at the respective enterprises [2]. Many researchers investigate the possibilities of waste utilization in the industrial production of construction materials [2–11]. These studies address the technological, environmental, and economic aspects of using waste materials as components for bricks, concrete, ceramics, and other construction products. The authors analyze the effects of additives on the physical and mechanical properties, resistance to external influences, and thermal stability of the final product and assess the prospects for scaling such solutions in sustainable construction and resource-saving technologies.

The production of building products and structures requires large reserves of natural raw materials. Some studies have shown that the porosity and pore morphology of ceramic materials can be adjusted by simply changing the content of waste glass powder, thereby affecting the density and compressive strength of ceramic materials. In this connection, a new strategy for recycling waste glass has been proposed, utilizing waste glass powder as a raw material for making lightweight and high-strength porous ceramic materials with self-cleaning properties [12, 13].

In Kazakhstan and Central Asia, loess clay is used in large quantities to produce ceramic wall bricks. Its main distinguishing feature is the high content of finely dispersed calcium carbonate. Loess clays are found in surface deposits, which allows for open-pit mining. Therefore, these clays are accessible for application in brick production. The composition of loess is dominated by dust particles (0.05–0.005 mm), the content of which reaches 80% by mass, and the rest is composed of clay (less than 0.005 mm) and fine particles (0.05–0.25 mm).

Loess clays contain significant amounts of carbonates. If carbonates are finely dispersed and distributed uniformly throughout the mass during firing, they react with clay minerals, chlorites, and micas to form calcium silicates, improving the product's mechanical properties. The presence of carbonates in the form of large inclusions is a common phenomenon. The dissociation of large $CaCO_3$ inclusions leads to the formation of pieces of free calcium oxide in the product's structure.

The plasticity of the clay raw material is important for brick molding and is responsible for forming a dense structure of the raw material. The physical, mechanical, and technological properties of clay ceramic products depend on characteristics, such as mineralogy [14], chemistry, particle size distribution, and plasticity [15], and the firing conditions: the temperature, temperature increase rate, and atmosphere in the kiln [16]. Mathematical tools have only recently started to be used in this field to evaluate the influence of raw material properties and process parameters on the quality of the final product [17]. Mathematical modeling has proven effective for determining the influence of process parameters on groups of dependent parameters that are essential in assessing the quality and performance of products [18, 19].

Adding a small amount of sand containing montmorillonite to clay allows for plastic molding. The inclusion of glass in the clay significantly reduces the sintering time of the brick to 8 hours and changes its strength properties [20].

Over the past few decades, materials science has developed a new direction of research and practice. This is connected with the advent of a new type of material involving the formation of so-called nanostructures.

Manipulation of nano-objects with the help of special technologies has made it possible to create fundamentally new materials and structures. The unusual properties of these materials are shaped by the characteristics of individual particles and their collective behavior. Furthermore, nanomaterials can be used not only in their pure form. Adding such particles to other materials can, in principle, also give the materials specific properties that they did not possess before.

Clay minerals, or smectites, which are the main components of the widely available bentonites, possess almost all the properties of natural nanoscale particles. So far, they have been used mostly spontaneously in the manufacture of construction materials, ceramics, and plastics, as additives in metallurgy and foundries, and in the form of suspensions in hydraulic construction and drilling operations [21].

While the mineralogy, plasticity, and firing behavior of clay-based ceramics have been extensively studied [14–21], and while individual additives such as montmorillonite or waste glass have been examined, the combined influence of these additives on low-grade loess clays remains insufficiently explored. In particular, almost no research has addressed how bentonite suspensions affect compaction, drying sensitivity, and microstructural stability. Therefore, the mechanisms through which waste glass and bentonite jointly improve the ceramic properties of loess-type raw materials remain poorly understood. This gap is especially relevant for Kazakhstan, where no effective technological approaches have yet been proposed for the combined use of these additives in ceramic brick production. The focus of this study is to investigate the possibility of using waste glass in combination with low-grade loess clays in West Kazakhstan to produce ceramic bricks. Today, West Kazakhstan has one of the largest deposits in Kazakhstan, the

Pogodaevsky deposit, with a clay reserve of over 6,181 thousand m^3.

This work aims to develop raw material composition and the respective technological approach that will increase the physical and mechanical characteristics of products while reducing their environmental impact.

2 Materials and Methods

The present study is aimed at evaluating the possibility of using waste glass and bentonite clay as additives to improve the quality of ceramic bricks made from low-grade loess clays of West Kazakhstan.

As the main clay component, we used clay from the Rubizhinsky deposit and bentonite clay from the Pogodaevsky deposit in West Kazakhstan. The fluxing additive was waste glass from bottle glass, pre-washed, cleaned of labels, crushed, and sieved to a fraction of 0.063–1.25 mm.

Bentonite was used in two forms: powder (dried and ground to a specific surface area of 1,000–1,200 cm^2/g) and suspension with a density of 1.3–1.4 g/cm^3. Bentonite samples were taken from stacks of the material stored in a warehouse using the scooping method. The sample was collected with a scoop at a depth of at least 30 cm from a total of 20 points. At each point, 5–6 pieces weighing about 60 g each were taken.

Samples of clay loam were collected from four separate points in the Rubezhinsky deposit. The point samples, each weighing 6 kg, were mixed to obtain a combined sample.

3 Chemical and Mineralogical Compositions of Raw Materials

The chemical and mineralogical composition of the studied raw components was determined on a scanning electron microscope JSM-639LV by “JEOL” with an energy dispersive analysis attachment INSA Energy by “OXFORD Instruments” (Tables 1 and 2).

Table 1. Chemical composition of bentonite clay from the Pogodaevsky deposit in West Kazakhstan

Raw Material	Oxide Content, Mass (%)							
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	Na_2O	LOI
Bentonite clay	61.51	17.06	2.27	3.21	6.36	1.27	3.57	6.75

Table 2. Chemical composition of clay loam from the Rubezhinsky deposit

Raw Material	Oxide Content, Mass (%)												
	SiO_2	Al_2O_3	TiO_2	CaO	MgO	Fe_2O_3	P_2O_5	F	SO_3	CO_2	Na_2O	K_2O	LOI
Clay loam	55.16	14.3	–	13.2	3.2	7.3	–	–	2.81	–	–	2.6	14.3

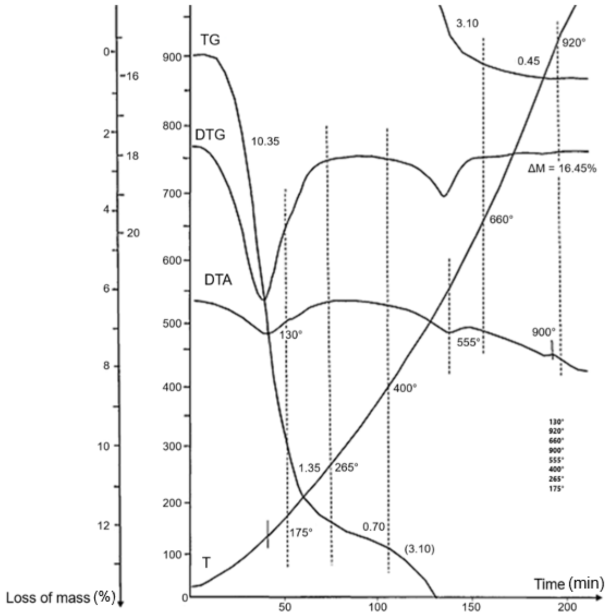

Figure 1. Derivatogram of the bentonite sample

The plasticity of clay materials was established by determining the lower liquid limit and the upper plastic limit according to GOST 9169-75.

To investigate the mineral composition and physical and mechanical characteristics of bentonite, thermal tests were carried out. The tests were performed on derivatographs OD-102 and Q-1000 with automatic recording of three curves: the thermogravimetric curve (TG), the differential thermogravimetric curve (DTG), and the differential thermogravimetric analysis curve (DTA) (Figure 1). The precision of the analysis was 0.3 mg. Because the bentonites of the studied deposit contain a significant amount of iron, up to 10%, which can be oxidized by heating, several control samples were tested under a nitrogen atmosphere.

The chemical composition of clay loam from the Rubezhinsky deposit is presented in Table 2.

The microstructure of clay loam from the Rubezhinsky deposit, West Kazakhstan, at different magnifications is shown in Figure 2.

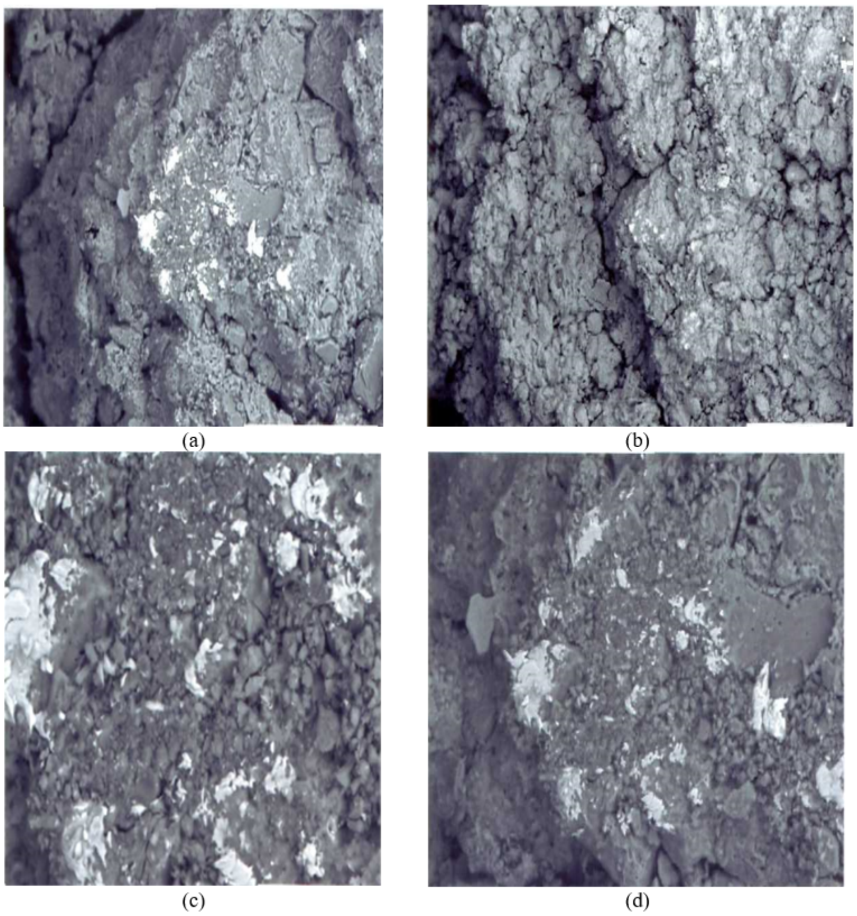
(a) (b) (c) (d)

Figure 2. Microstructure of clay loam from the Rubezhinsky deposit, West Kazakhstan, at different magnifications: (a) magnification ×100; (b) magnification ×500; (c) magnification ×1,000; (d) magnification ×2,000

The radiograph and thermogram of clay loam from the Rubezhinsky deposit are presented in Figures 3 and 4.

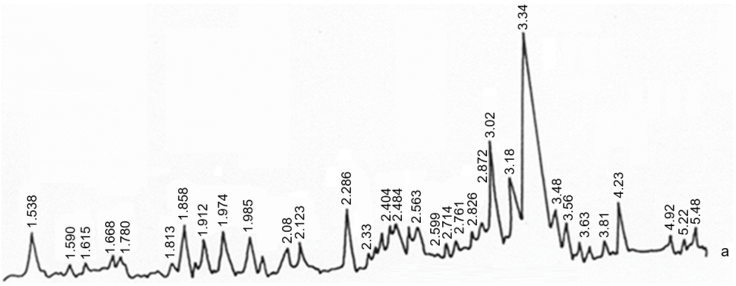

Figure 3. Radiograph of clay loam from the Rubezhinsky deposit

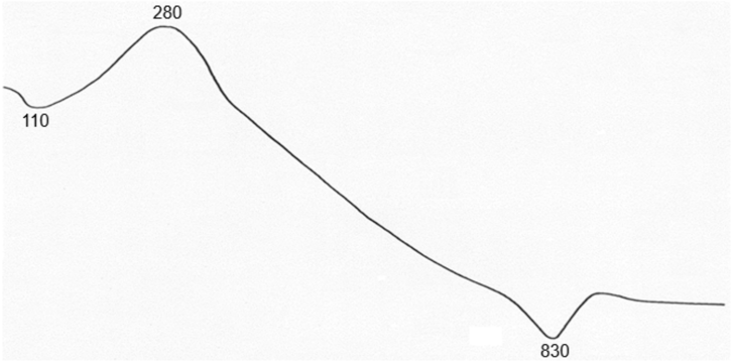

Figure 4. Thermogram of clay loam from the Rubezhinsky deposit

4 Technological Preparation of Raw Bricks and Methods of Determining Physical and Mechanical Properties

The studies were conducted on two three-component raw material systems: "clay loam-bentonite powder-waste glass" and "clay loam-bentonite suspension-waste glass".

The following component content limits (in mass %) were chosen as the investigated area:

(1) Clay loam 75%–97%, bentonite powder 3%–10%; waste glass 5%–15%.

(2) Clay loam 70%–95%, bentonite suspension 15%–25%; waste glass 5%–15%.

To create the ceramic composition in the loess clay-bentonite suspension-waste glass system, bentonite clay was first made into a suspension with a density of 1.3–1.4 g/cm^3. Clay loam and waste glass were combined, and bentonite suspension in the amount of 25%–30% of the mass of dry components was added, after which the components were mixed to create the ceramic composition. The resulting ceramic mass was dried to 8%–10% moisture content.

To prepare the ceramic composition in the loess clay-bentonite powder-waste glass system, bentonite clay was dried at 90–100 °C to a constant weight. The dried clay was ground in a laboratory ball mill to a specific surface area of 1,000–1,200 cm^2/g. Waste glass was crushed and sieved on 0.063–1.25 sieves. All components were then blended into a homogeneous mixture.

Samples in the shape of 5 × 5 × 5 cm cubes were prepared from the raw material mixtures using the semi-dry pressing method. The moisture content of the masses was 8% of the mass of dry components, and the pressing pressure was 15–20 MPa.

The moisture content of the raw mixtures was monitored on an MX-50 moisture analyzer.

The raw material mixtures were first molded by semi-dry pressing at a pressure of 15–20 MPa. The obtained molded products were fired without pre-drying in a muffle furnace at temperatures ranging from 600 to 1,100 °C. The rate of temperature increase was 1.5–2 °C per minute.

The parameters examined for optimizing ceramic masses were: raw brick strength, which characterizes the molding properties of the mass, average product density and water absorption as indicators of the physical properties of the mixture, and compressive strength of finished products as a criterion of product quality.

Air-dry shrinkage of the clay masses was determined by the formula:

$$S_{\text{air}} = [(l_0 - l_1)/l_0] * 100\% \tag{1}$$

where, l_0 = length of the freshly molded sample; l_1 = length of the sample after drying (EN 771-1:2020).

Firing shrinkage was expressed in percentages of the length of the molded sample:

$$S_{\text{fire}} = [(l_1 - l_2)/l_0] * 100\% \tag{2}$$

where, l_0 = length of the freshly molded sample; l_1 = length of the sample after drying; l_2 = length of the sample after firing (EN 771).

Compressive strength was determined by testing a series of samples (at least 3) on a PGM-500MG4 hydraulic press. The press automatically calculates compressive strength by formula:

$$R_{\text{comp}}\ (\text{MPa}) = \frac{P}{F} \tag{3}$$

where, P = breaking force, N (kgf); F = cross-sectional area of the sample (m^2, cm^2).

Frost resistance was tested in a hot and cold chamber equipped with a microprocessor. The temperature in the chamber was set at -17 °C for freezing and 22 °C for unfreezing. The design of the heat and cold chamber ensures high accuracy in maintaining the set temperatures and a high degree of reliability in operation.

To ensure the reliability of the frost resistance results, at least 25 freeze-thaw cycles were carried out on each series of fired brick samples according to EN 772-22:2011 and GOST 7025-91 standards. Each cycle of freezing and thawing consisted of 4 hours of freezing at -17 ± 2 °C followed by 2 hours of thawing in water at 22 ± 2 °C. Every five cycles, the samples were visually inspected for the appearance of cracks, scaling or delamination of the surface, mass loss and strength loss. Frost resistance was quantified by determining both the residual compressive strength and the mass loss percentage after the completion of the test series. The material was considered frost-resistant if the reduction in compressive strength did not exceed 20% and mass loss remained below 5% relative to the initial values. These parameters allowed assessing not only visible damage but also structural degradation of the ceramic matrix during cyclic freezing and thawing.

Before testing, the fired samples were brought to a constant mass and then saturated with water for 24 hours, as required by EN 772-22:2011. Frost-thaw cycling was carried out in a programmable climatic chamber (Binder MK 240), which maintains the set temperature profile with a deviation not exceeding ± 1.5 °C.

Water absorption was determined on fired samples according to EN 771-1:2020. On average, three specimens were dried to constant weight. Then they were placed in a vessel filled with water at a temperature of (20 ± 5) °C so that the water was 2–10 cm above the samples. The ceramic samples were kept submerged for 48^{+1} hours. Once saturated with water, the samples were taken out, wiped with dry cloth, and weighed. Water absorption (W) was determined as follows:

$$W = [(m_l - m) / m] * 100 \tag{4}$$

where, m_l = mass of the sample saturated with water (g); m = mass of the sample dried to constant weight (g).

The value of water absorption was taken as the arithmetic mean of the obtained results with an accuracy of 1%. The plasticity of the clays was determined by the liquid limit (LL) and plastic limit (PL), which are used as benchmarks to quantify the plasticity of clays by determining, respectively, the upper and lower limits of water content at which the clay (or soil) is plastic. The plasticity index (PI) is the difference between these two parameters, as defined by Casagrande [22] and ASTM standards [23, 24].

To assess whether the differences in compressive strength between the six compositions at the optimal firing temperature were statistically significant, a non-parametric Kruskal–Wallis test was applied. This method does not require normally distributed data and is appropriate for small sample sizes and heterogeneous ceramic materials. The analysis was carried out using grouped replicate measurements of compressive strength, and significance was established at $p < 0.05$.

To get as close as possible to factory conditions and subsequently put the bricks into production, experiments were carried out to determine the firing parameters and to draw up the firing schedule.

To determine the firing parameters, standard bricks (250 × 120 × 65 mm) were molded in laboratory conditions by semi-dry pressing using optimal charge and fractional compositions of composite masses. The pressing pressure was 15 MPa, and the humidity of the masses was 8%–10% of the mass of dry components.

Given the low coefficient of sensitivity to drying of the tested masses, the molded bricks were fired without preliminary drying in a special electric kiln with carbide-silicon heaters. The temperature increase rate was regulated by autotransformers.

At the start of firing, the molded samples were dried directly in the firing furnace.

To prevent the raw bricks from cracking while drying, the starting temperature was set at 50 °C and gradually increased to 200 °C at a rate of 25 °C per hour. The duration of drying for the studied ceramic compositions was 3 and 3.5 hours.

The products were then fired with a temperature rise rate of 66–67 °C per hour at up to 400 °C, because the addition of bentonite clay increases the crack resistance of the ceramic mass, so this temperature zone becomes less dangerous.

Further firing of the products was performed according to calculations at a slower temperature increase rate of 34.6–35.7 °C/h to avoid all kinds of deformations because of the onset of the main phase transformations, sintering processes, and crystallization in the masses, which cause volumetric changes in the products.

Given that bottle glass enters its liquid phase at approximately 1,200–1,400 °C, the optimal firing temperature and resting time for the products were estimated based on the homogeneity of sintering in the fracture of the product and the ratio of crystalline and glass phases, which provides the required physical and mechanical properties of the finished product.

As a result, the optimal ratio of crystalline phase and glass phase and high strength characteristics were achieved in samples fired at 900–950 °C.

The studied properties of ceramic masses included the drying sensitivity coefficient, air-dry shrinkage, the strength of the raw brick as a criterion of drying and molding properties, firing shrinkage, and compressive and flexural strength as indicators of product quality.

Sensitivity to drying is determined by resistance to cracking in the drying process. The appearance of cracks is associated with tensions arising from variations in shrinkage across the cross-section and surface of the product.

Cracks form when the emerging tensions exceed the ultimate tensile strength of the material. With increasing strength of clays, their crack resistance typically increases. Therefore, the addition of highly plastic clay to clay with a high sand content in some cases improves the quality of dried products [25, 26].

The drying sensitivity coefficient was determined by an express method proposed by Chizhsky [27], which relies on the duration of irradiation of a wet clay sample with a powerful heat flux until cracks appear on its surface. This method is distinguished by the simplicity of its procedure and equipment. Figure 5 shows a circuit diagram of the installation recommended for determining the time of irradiation Z_0.

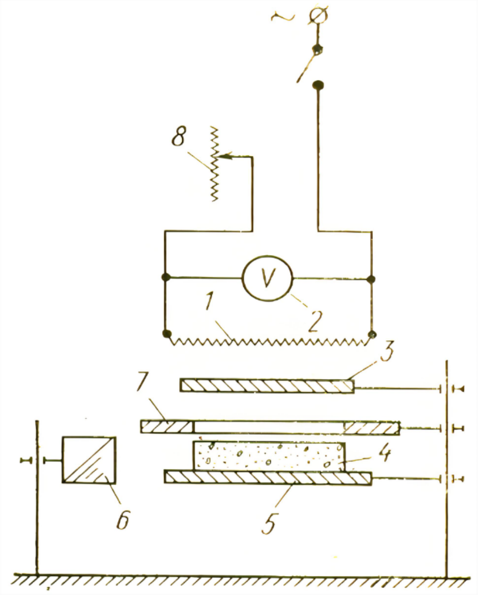

Figure 5. Circuit diagram for the express method of determining the drying resistance of clays

Using this circuit, the installation for determining the coefficient of sensitivity to drying was assembled at the laboratory of Zhangir Khan University. A laboratory autotransformer was used to regulate the heating power of the electric stove.

The source of irradiation can be a 400 W electric stove (1). The sample (4) in the shape of a 55 × 55 × 16 mm bar made of the target mass with a normal molding moisture content is placed on the lifting table (5), using which a specific distance between the radiator and the sample is set. The mirror (6) provides a full view of the sample. The screen (7) with an opening of 55 × 55 mm serves to prevent the side surface of the sample and the lifting table from heating up. A constant electric voltage is maintained according to the voltmeter (2) by adjusting it with the rheostat (8). The power of the heat flux is periodically monitored with a calorimeter (thermal probe). The solid screen (3) protects the tested sample and the table from heating up prematurely while preparing the unit for testing (heating the stove, changing samples, etc.).

According to Chizhsky [27], under a heat flux of 7,000 W/m^2 and with a 60 mm distance between the radiator and the sample, Z_0 equals 35–50 seconds for clays with high drying resistance, 60–80 seconds for medium resistance, and 90–130 seconds for low resistance.

5 Results and Discussion

5.1 Chemical and Mineralogical Composition of Raw Materials

Clay loam belongs to the group of acidic raw materials by the content of Al_2O_3 and to low-melting materials by fire resistance. By the content of Fe_2O_3, it has a high content of coloring oxides.

Regarding mineralogical composition, clay loam from the Rubezhinsky deposit (Figure 2a) contains up to 12% montmorillonite in the form of mixed-layer formations with hydrous mica and kaolinite.

Among the crystalline phases, clay from the Chagansky deposit also contains quartz with d-spacings of 4.23, 3.34, 1.974, 1.813, and 1.538 Å, feldspar with d-spacings of 3.18 and 2.286 Å, calcite with d-spacings of 3.02, 2.018, and 1.912 Å, and hematite with d-spacings of 1.839, 1.686, and 1.590 Å. It was further established that clay from the Pogodaevsky deposit, by its refractory properties, belongs to the easy-melting category, by Fe_2O_3 content to clays with a high content of coloring oxides, and by Al_2O_3 content to acidic raw materials. The mineralogical composition of bentonite clay (Figure 6) is represented mainly by montmorillonite with d-spacings of 5.06, 4.46, 3.79, 3.06, 2.455, 2.28, 2.127, 1.977, 1.817, and 1.675 Å.

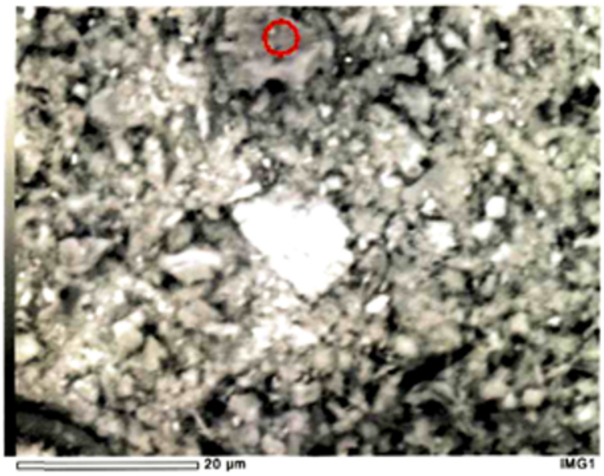

Figure 6. Microstructure of bentonite clay from the Pogodaevsky deposit

Several endothermic and exothermic effects can be observed on the DTA curve of bentonite clay (Figure 7). The endothermic effect at 125 °C is related to the loss of adsorption water, and at 545 °C corresponds to the removal of chemically bound water. The endothermic effect at 885 °C coincides with the decomposition of calcite to release CO_2. The exothermic effect at 300 °C is caused by the burnout of organic impurities, and at 915 °C by the crystallization of high-temperature phases.

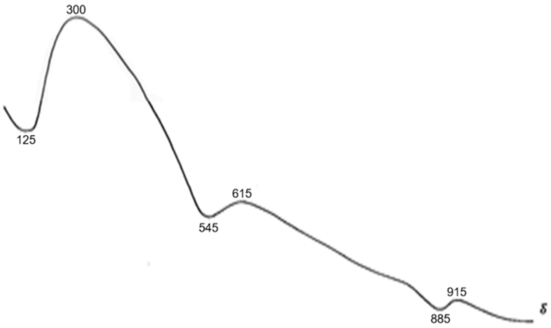

Figure 7. Thermogram of bentonite clay from the Pogodaevsky deposit

The analysis of the obtained TG, DTG, and DTA curves solved several objectives: a) clarifying the phase composition of the sample and the content of the clay component and montmorillonite in particular; b) evaluating the thermal stability of bentonite; c) solving several practical problems: e.g., determining the intervals of release of different types of water, determining the effect of firing temperature on the character of clay rehydration, and thus establishing permissible drying temperatures for bentonite, determining the effect of drying temperature on swellability, etc.

Mineral composition was determined by analyzing the synchronously recorded DTG and DTA. In total, the thermal curves of more than 30 samples were analyzed. The thermograms of bentonite clay samples show three main thermal effects characteristic of montmorillonite: at 130, 545, and 850 °C (Figure 1).

Virtually all thermal curves show two distinct endothermic and one very weak exothermic effect at temperatures above 800 °C (Figure 1). Some curves also show an endothermic effect at 300 °C, which indicates the presence of goethite.

Exothermic effects in the 250–350 °C range point to the presence of pyrite.

However, the main endothermic effects are associated with the presence of clay minerals, particularly smectite. The first strong endothermic effect corresponds to the interval of $\sim$125 °C and is associated with the release of interpackage water from montmorillonite layers. The montmorillonite component proper is characterized by an interval of 60–275 °C. The continuation of the effect into higher temperatures indicates the presence of hydrous mica both as an independent phase and in a mixed-layer mineral. In this case, in the interval of 20–275 °C, interpackage water is expelled from montmorillonite layers, and then in the interval of 250–350 °C, it is separated from the hydrous mica component. The bend indicates the separation of water from the hydrous mica component. The bend in the region of 200–250 °C indicates Ca-Mg cation exchange.

The second endothermic effect, around 500–560 °C, characterizes the release of so-called constitutional water or hydroxyl. In this case, a partial amorphization of the substance takes place. The maximum corresponds to about 500–560 °C. This effect characterizes the thermal stability of the mineral and depends on the ratio of Al, Fe, and Mg in octahedral lattice layers and the positions of octahedra within the octahedral layer. A1 isomorphous substitution of Mg and Fe leads to a decrease in the temperature of this endothermic effect: in this case, the octahedral layer is destroyed at a relatively low temperature. Virtually all smectites of the studied sites are characterized by high iron content (8%–12%). This peculiarity of the chemical composition of bentonite explains its low thermal stability. On the contrary, in A1 and Mg montmorillonites, this maximum can be found at 600–800 °C. In some cases, there may be two maxima (one intense and the second weak) in the interval of the second endothermic effect. This effect can be associated with the position of an individual octahedron or a group of octahedrons in relation to their predominant position. This principle distinguished cis and trans octahedra.

The third effect is associated with the release of a small amount of remaining structural water (about 1%–1.5%) and the destruction of the montmorillonite structure. The weak exothermic effect at 1,000 °C indicates the presence of hydrous mica, which may be present as a free phase or participate in the formation of a mixed-layer mineral. In the same temperature region, there is another exothermic effect associated with the destruction of kaolinite group minerals (halloysite, kaolinite).

The thermal effects identified on the DTA curves correspond well to those reported for montmorillonitic clays in earlier studies. The endothermic peaks near 120–130 °C and 500–560 °C, as well as the higher-temperature effects linked to carbonate decomposition, fall within the ranges described by Celik [15] and Hammami-Ben Zaied et al. [16], confirming the similarity in dehydration and dehydroxylation behaviour. Minor deviations in peak intensity are consistent with the higher iron content of the Pogodaevsky bentonite reported in the present work.

As demonstrated in Figure 2, clay loam from the Rubezhinsky deposit contains up to 12% of the montmorillonite component in the form of mixed-layer formations with hydrous mica and kaolinite. The effects of these minerals can be observed on the radiograph in Figure 3. Among the crystalline phases, the clay also contains quartz with d-spacings of 4.23, 3.34, 1.974, 1.813, and 1.538 Å, feldspar with d-spacings of 3.18 and 2.286 Å, calcite with d-spacings of 3.02, 2.018, and 1.912 Å, and hematite with d-spacings of 1.839, 1.686, and 1.590 Å.

The X-ray curve (Figure 4) of clay loam shows an endothermic effect at 120 °C associated with the removal of adsorption water, while the exothermic effect at 280 °C corresponds to the combustion of organic impurities. The endothermic effect at 830 °C coincides with the temperature of calcite decomposition with the release of carbon dioxide.

The results on clay plasticity show that bentonite clay has a plasticity of 26.5, which puts it in the category of high plasticity clays. On the contrary, clay from the Rubezhinsky deposit has a plasticity of 9.6, which characterizes it as a low-grade clay.

The experiment to determine drying sensitivity coefficients by the Chizhsky method [27] demonstrates that bentonite belongs to the low-sensitivity group with 102 seconds, while the Rubizhinsky loam is highly sensitive to drying with 65–70 seconds.

The introduction of bentonite and waste glass increased the drying sensitivity coefficient of the developed compositions, indicating reduced cracking susceptibility during molding and drying (Figure 8). At the same time, the addition of waste glass contributed to improved sinterability and enhanced frost resistance of the fired products, as shown in Figure 9.

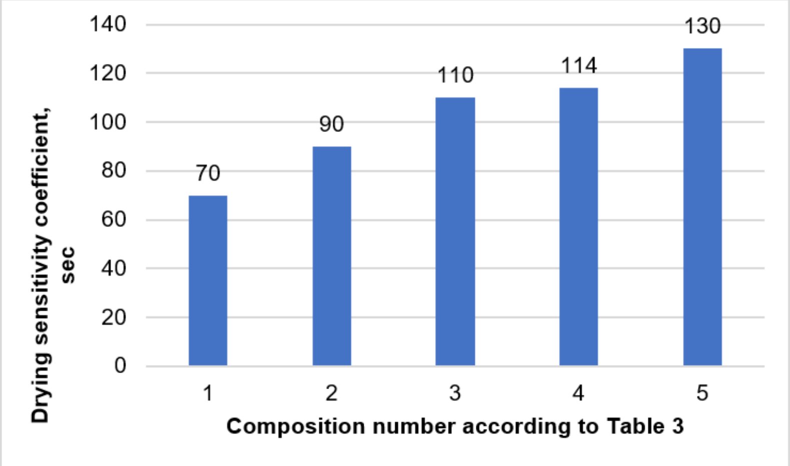

Figure 8. The influence of adding bentonite and waste glass on the drying sensitivity of the studied compositions

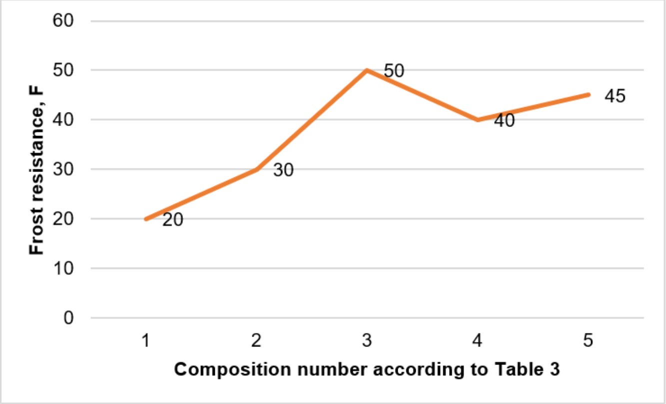

Figure 9. The influence of adding bentonite and waste glass on the frost resistance of the studied compositions

The rise in the sensitivity coefficient suggests a positive effect of the bentonite and waste glass additives in the compositions (Table 3), which allows the raw material to be moved from the category of highly sensitive to low sensitivity. This provides greater opportunities to reduce cracking during molding and subsequent firing. The addition of waste glass in 0.063–1.25 fractions contributes to the sinterability of the product, which leads to improved frost resistance.

Table 3. Mix proportions of different samples (%)

Clay Loam	Bentonite Powder	Bentonite Suspension	Waste Glass
80	–	15	5
70	–	20	10
60	–	25	15
92	3	–	5
83	7	–	10
75	10	–	15

5.2 Influence of Firing Temperature on the Physical and Mechanical Properties of Samples from the Developed Compositions of Ceramic Masses

Heat treatment was applied to samples with the optimal compositions of raw materials: “clay loam-bentonite powder-waste glass” and “clay loam-bentonite suspension-waste glass”. The mass fractions of the components are given in Table 3.

The composite raw material containing bentonite suspension (Figure 10) has a 10%–15% higher average density. This increase comes from the fact that the colloidal particles of the suspension can push apart the intergranular space of the clay loam, filling all the micro- and macropores of the clay mass. As a result, pressing achieves the greatest compaction. Considering the melting point of glass, during firing, the melting of glass and the formation of the semi-liquid phase contributed to the sintering of clay particles, enhancing strength properties.

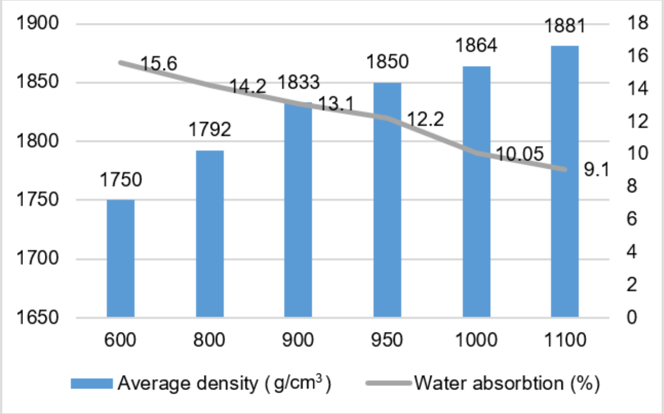

Figure 10. Dependence of the average density and water absorption of the “clay loam-bentonite suspension-waste glass” composite material on firing temperature

The introduction of powdered bentonite results in tension within raw bricks while drying due to the difference between water consumption and yield, as well as the swelling of clay loam and bentonite. The difference in the linear dimensions of the samples is 35% (Figures 11 and 12).

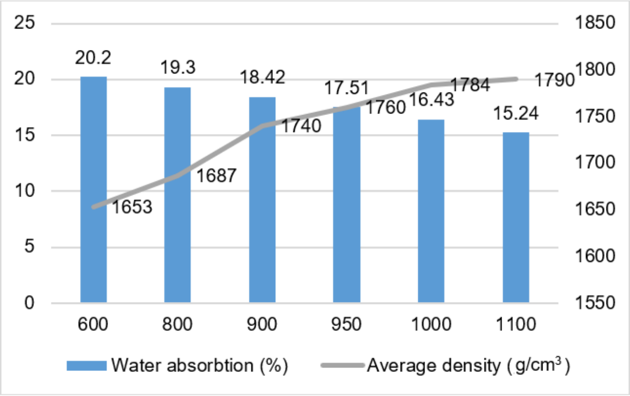

Figure 11. Dependence of the average density and water absorption of the "clay loam-bentonite powder-glass" composite material on firing temperature

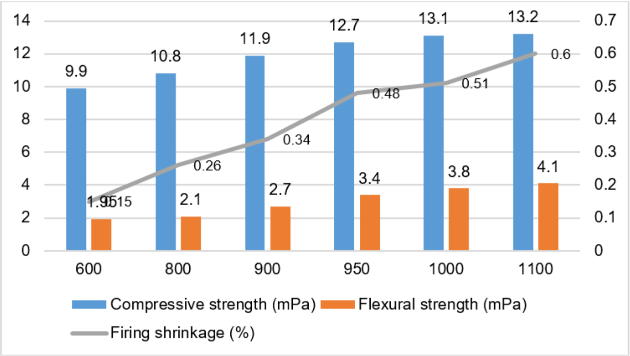

Figure 12. Dependence of the compressive and flexural strength and firing shrinkage of the "clay loam-bentonite suspension-waste glass" composite material on firing temperature

The analysis of changes in the physical and mechanical properties of heat-treated samples at 600–1,100 °C shows that strength increases only slightly at 600 °C. As the firing temperature is further raised, an increase in strength is observed in both compositions. Specifically, in the temperature range of 600–900 °C, the strength values increase to 8.4 MPa (bentonite powder-waste glass) and 10.1 MPa (bentonite suspension-waste glass) (Figures 10 and 13). Firing shrinkage is greater in composites with bentonite suspension than with bentonite powder (0.05%–0.07% vs. 0.15%–0.34%), which testifies to an increase in sinterability for the "clay loam-bentonite suspension-waste glass" composition (Figures 11 and 12).

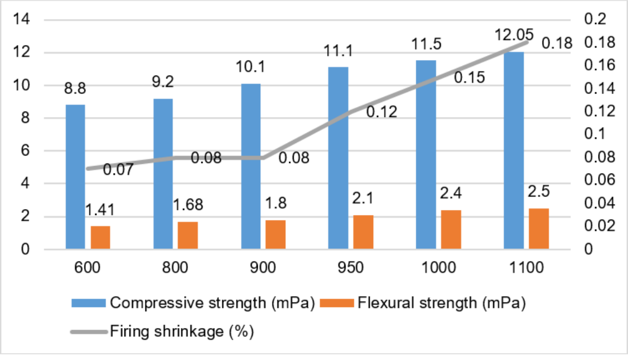

Figure 13. Dependence of the compressive and flexural strength and firing shrinkage of the "clay loam-bentonite powder-waste glass" composite material on firing temperature

When the ceramic compositions were fired in the range of 900–1,000 °C, a significant increase in strength values was observed. The maximum strength in this temperature range was achieved by ceramic compositions with bentonite suspension and amounted to 11.9–13.1 MPa, which is 9% more compared to the composite with powdered bentonite.

Importantly, the enhanced strength of the suspension composite is accompanied by shrinkage (0.34%–0.51%), suggesting an intensification of the sintering process in ceramic masses with bentonite suspension.

When the temperature was raised to 1,100 °C, the degree of sintering was significantly higher in samples from the suspension-containing ceramic composition, as evidenced by the high strength of the samples (13.2 MPa) and moderate firing shrinkage (0.6%).

The Kruskal–Wallis test showed that the variation in strength across the compositions was significant ($H = 22.06$, $df = 5$, $p < 0.001$). It indicated that the improvements observed in the suspension-modified mixtures can't be attributed to random experimental scatter. The highest ranks were consistently associated with samples containing bentonite suspension, reflecting the greater densification and enhanced sintering behaviour. In contrast, mixtures incorporating bentonite in powder form showed lower ranks, which agrees with their more limited compaction and higher porosity. These statistical results reinforce the experimental findings derived from Figures 12 and 13: the transition from powder to suspension activation produces a measurable and systematic strengthening effect across all temperatures, with the most pronounced difference occurring near 900–1000 °C, where feldspar crystallization and glass-phase formation intensify.

The strong agreement between mechanical tests, statistical analysis, and microstructural observations (presented in Section 5.3) demonstrates that the suspension-based approach provides a more efficient modification route for low-grade loess clays, enabling the formation of a denser ceramic matrix with superior load-bearing capacity.

5.3 Analysis of Structure Formation Processes in Ceramic Composites

The structure of real materials, including ceramic ones, is examined on two levels: micro and macro. These levels in the internal structure of matter have different effects on the properties of the ceramic material.

The solid structure of ceramics, which offers high-performance properties, is formed at the firing stage. In this case, phase formation processes are largely determined by the composition of the charge and the properties of its components.

Phase formation processes in clay and with different combinations of additives have been researched thoroughly [28–33].

Our research focused on the optimal compositions of our newly developed masses. For this purpose, cylindrical samples (d = 16 mm, h = 25 mm) were molded from the composite ceramic masses and subjected to heat treatment. The maximum firing temperature and the intervals between the corresponding temperatures were chosen considering DTA curves and charge composition.

The samples were rested for 1 hour at each end temperature. After heat treatment, the samples were subjected to petrographic analysis with a microscope in the form of thin sections, submerged in immersion liquids, and using X-ray diffraction (XRD) analysis (Figures 14 and 15).

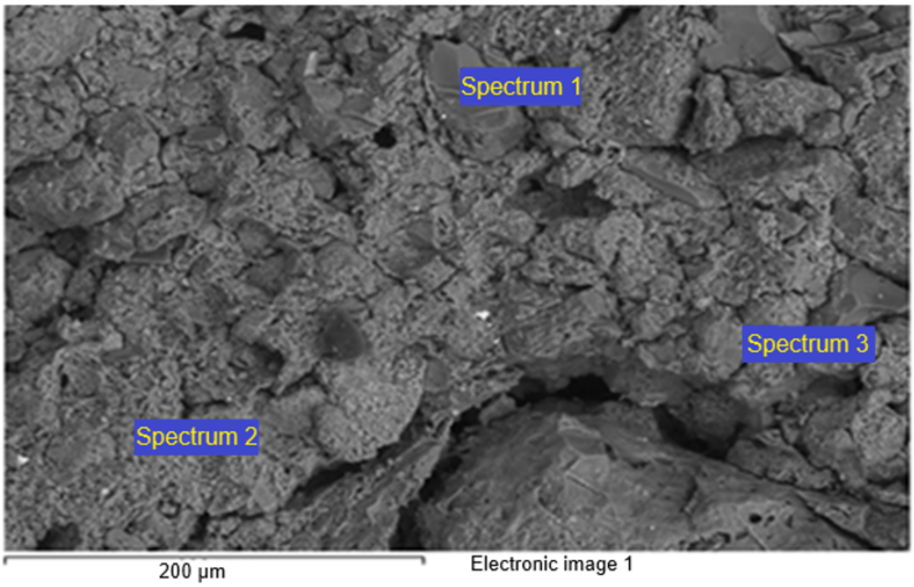

Figure 14. Microstructure of the "clay loam-bentonite-waste glass" ceramic composite (magnification ×2,000)

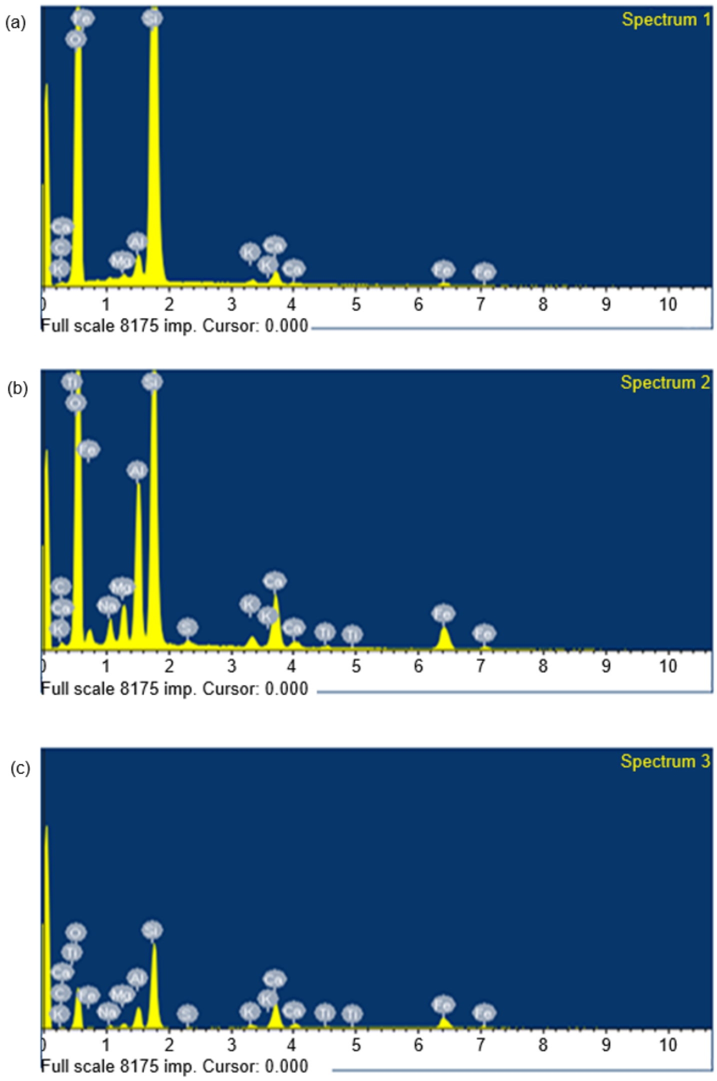

Figure 15. Spectra of ceramic composites at different sites: (a) site 1; (b) site 2; (c) site 3

The results of the processing parameters are summarized in Table 4.

Table 4. Results of chemical elemental analysis of the sample from the ceramic composition "clay loam-bentonite-waste glass" by sites

Spectrum	In stat.	C	O	Na	Mg	Al	Si	S	K	Ca	Ti	Fe	Total
Spectrum 1	Yes	1.97	62.56	–	0.21	0.92	32.50	–	0.24	1.00	–	0.61	100.00
Spectrum 2	Yes	0.00	58.45	2.02	2.26	7.84	19.70	0.25	0.76	4.07	0.19	4.45	100.00
Spectrum 3	Yes	0.00	47.08	1.13	1.41	3.15	12.33	0.23	1.05	10.25	0.57	10.64	100.00
Sum-spectrum	Yes	0.00	53.65	1.23	1.50	6.74	23.78	0.18	1.68	6.46	0.35	4.43	100.00
Maximum	–	1.97	62.56	2.02	2.26	7.84	32.50	0.25	1.68	10.25	0.57	10.64	–
Minimum	–	0.00	47.08	1.13	0.21	0.92	19.70	0.18	0.24	1.00	0.19	0.61	–

Note: all results are in weight %.

The mineralogical composition of the fired "clay loam-bentonite-waste glass" composite, including the identified quartz and feldspar-related phases, is presented in Table 5. Albite ($NaAlSi_3O_8$) and anorthite ($CaAl_2Si_2O_8$) play a key role in determining the mechanical performance of the fired ceramics because they belong to the feldspar group minerals, which act as a structural reinforcement of the silicate network [34, 35]. Their formation occurs in the firing process through a solid-solid state reaction between silica, alumina, and calcium oxide, resulting in a crystallized region within the glassy matrix. The interlocking of these lattices across the grain boundaries increases the load transfer between the grains and inhibits the development of cracks, thus increasing the compressive and flexural strength of bentonite-glass-modified compositions. The simultaneous formation of albite and anorthite reduces the residual porosity of the system, thereby minimizing water absorption and increasing frost resistance.

Table 5. Mineralogical composition of the "clay loam-bentonite-waste glass" composite

Sample Number	Code of the Mineral	Mineral Name	Chemical Formula	Content (%)
1	01-070-2517	Quartz low–theoretical	SiO_2	28
2	00-041-1480	Albite, calcian, ordered	$(Na,Ca)Al(Si,Al)_3O_8$	7
3	01-074-2217	Dialuminium oxide silicate	Al_2SiO_5	53
4	01-083-1614	Albiteite, high, sodium tecto-alumotrisilicate	$Na(AlSi_3O_8)$	12

The increased strength of the modified samples is associated with the appearance of albite and anorthite phases identified by XRD. These feldspars form during firing and take part in consolidating the ceramic framework by strengthening contacts between adjacent grains. Their presence reduces the continuity of pores, restricts the development of microcracks, and improves the transfer of mechanical loads through the structure. In compositions containing bentonite suspension, the denser packing of raw particles creates more favorable conditions for the crystallization of these phases, which corresponds to the higher compressive strength values and reduced water absorption recorded for these samples. Consequently, the formation of albite and anorthite should be regarded as a central factor governing the improved mechanical behaviour of the studied ceramic masses.

The comprehensive and comparative analysis of microstructure and changes and distribution of the main silicate-forming chemical elements in the ceramic masses showed that the introduction of bentonite powder with a high specific surface area (1,200–1,500 cm^2/g) together with waste glass significantly changes the general microstructure morphology of the "clay loam-bentonite-waste glass" composite. This is evidenced by electronic images of clay loam and the ceramic composite at different magnifications.

The microstructure of the ceramic product made of non-conditioned clay and waste glass modified with bentonite clay is distinguished by homogeneity and more uniform and dense interlocation of clay aggregates due to the enveloping of larger particles of loess clay by fine particles of highly plastic bentonite clay and the uniform distribution of glass particles.

Such interposition of two clays differing in physical, mechanical, chemical, and mineralogical compositions in the mixture with waste glass is ensured by the choice of optimal ratios of the constituent components and their specific surface area, as well as the technological methods of preparing raw materials considering the characteristics of loess clay, bentonite clay, and waste glass.

This is confirmed by the improved properties of ceramic samples at the stages of molding, drying, and heat treatment.

6 Conclusions

Based on the investigation of the physical, mechanical, chemical, and mineralogical characteristics of raw materials, the raw material composition "loess clay-bentonite clay-waste glass" was proposed for creating an effective production technology for high-quality ceramic wall bricks with semi-dry pressing.

The study found that the modified combinations of waste cullet and loess clay improve molding properties due to the ability of bentonite clay to self-disperse into the smallest particles when it interacts with water.

This study established that "waste glass-loess clay" mixture modified with bentonite clay suspension transforms the ceramic mass from highly sensitive to medium sensitive, allowing for boosting the drying process and molding raw bricks without defects.

The key patterns of structure and phase formation of ceramic composites in the temperature range of 600–1,100 °C. Comprehensive and comparative analysis of the microstructure and the changes and distribution of the main silicate-forming chemical elements in ceramic masses has shown that the introduction of bentonite suspension with a density of 1.3–1.4 g/cm^3 contributes to a significant change in microstructure morphology of the "clay loam-bentonite-waste glass" ceramic composite. The microstructure of the ceramic product modified with bentonite clay is characterized by homogeneity and more uniform and dense interposition of clay aggregates as a result of larger particles of loess clay being enveloped by finely dispersed particles of highly plastic bentonite clay.

Pure clay loam and the modified ceramic composite demonstrated significant differences in structure formation processes. Products from ceramic composites modified with bentonite clays and waste glass have an increased content of Si, Al, Na, and K owing to the chemical composition of bentonite clay and glass. This indicates the enrichment of loess clay with these chemical elements, accompanied by the stable formation of crystalline phases of albite and anorthite, which play the role of reinforcing minerals in the microstructure of ceramic products and give them high strength, frost resistance, and improved water absorption.

The results have important implications for further developing sustainable construction technologies. Bentonite suspension and recycled glass cullet can improve the mechanical performance of loess-based ceramics while minimizing the consumption of virgin raw materials and the amount of glass waste generated during building operations. The results of this research offer a realistic way towards achieving circular economy of industrial by-products in Kazakhstani construction. The developed composition and firing regime can be easily implemented at existing brick works with semi-dry pressing technology with no major changes in the production process. If implemented at scale, the approach could help reduce energy use and costs of raw materials as well as meet national and international needs for low carbon, resource-efficient, construction materials.

Thus, the findings also indicate that incorporating waste glass and local bentonite can reduce the use of primary raw materials and lower the environmental burden of ceramic production. Because the proposed compositions are compatible with standard semi-dry pressing lines, they can be introduced into industrial manufacture without modifying existing equipment.

Author Contributions

Conceptualization, S.M. and A.S.; methodology, S.M. and N.A.; software, A.M.; validation, A.S., A.B., and K.D.; formal analysis, N.A. and A.M.; investigation, S.M., N.A., and A.M.; resources, S.M. and A.S.; data curation, A.B. and K.D.; writing—original draft preparation, N.A. and A.S.; writing—review and editing, A.D. and A.Z.; visualization, A.M. and A.Z.; supervision, S.M.; project administration, A.S. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] FEVE The European Container Glass Federation, "European container glass industry on path to net zero calls for fast access to low carbon energy infrastructures," 2024. https://feve.org/decarbonisation-press-release

[2] D. Atzori, S. Tiozzo, M. Vellini, M. Gambini, and S. Mazzoni, "Industrial technologies for CO_2 reduction applicable to glass furnaces," *Thermo*, vol. 3, no. 4, pp. 682–710, 2023. https://doi.org/10.3390/thermo3040039

[3] B. S. da Fonseca, C. Galhano, and D. Seixas, "Technical feasibility of reusing coal combustion by-products from a thermoelectric power plant in the manufacture of fired clay bricks," *Appl. Clay Sci.*, vol. 104, pp. 189–195, 2015. https://doi.org/10.1016/j.clay.2014.11.030

[4] P. Muñoz Velasco, M. P. Morales Ortíz, M. A. Mendívil Giry, and L. Muñoz Velasco, "Fired clay bricks manufactured by adding wastes as sustainable construction material—A review," *Constr. Build. Mater.*, vol. 63, pp. 97–107, 2014. https://doi.org/10.1016/j.conbuildmat.2014.03.045

[5] S. N. Monteiro and C. M. Fontes Vieira, "On the production of fired clay bricks from waste materials: A critical update," *Constr. Build. Mater.*, vol. 68, pp. 599–610, 2014. https://doi.org/10.1016/j.conbuildmat.2014.07.006

[6] J. Malaiskiene and R. Maciulaitis, "Frost resistant ceramics from local raw materials and wastes," *Procedia Eng.*, vol. 57, pp. 739–745, 2013. https://doi.org/10.1016/j.proeng.2013.04.093

[7] J. Bolden, T. Abu-Lebdeh, and E. Fini, "Utilization of recycled and waste materials in various construction applications," *Am. J. Environ. Sci.*, vol. 9, no. 1, pp. 14–24, 2013. https://doi.org/10.3844/ajessp.2013.14.24

[8] L. Zhang, "Production of bricks from waste materials—A review," *Constr. Build. Mater.*, vol. 47, pp. 643–655, 2013. https://doi.org/10.1016/j.conbuildmat.2013.05.043

[9] S. P. Raut, R. V. Ralegaonkar, and S. A. Mandavgane, "Development of sustainable construction material using industrial and agricultural solid waste: A review of waste-create bricks," *Constr. Build. Mater.*, vol. 25, no. 10, pp. 4037–4042, 2011. https://doi.org/10.1016/j.conbuildmat.2011.04.038

[10] X. Zhao, J. X. Lu, X. Lv, V. Tian, M. Cyr, A. Tagnit-Hamou, and C. S. Poon, "Recycling of contaminated waste glass in ultra-high performance concrete: Impurities impact," *Constr. Build. Mater.*, vol. 437, p. 136971, 2024. https://doi.org/10.1016/j.conbuildmat.2024.136971

[11] J. García-Ten, M. Dondi, J. V. M. B. Vieira Lisboa, M. V. Cabedo, L. Pérez-Villarejo, E. Rambaldi, and C. Zanelli, "Critical raw materials in the global high-throughput ceramic industry," *Sustain. Mater. Technol.*, vol. 39, p. e00832, 2021. https://doi.org/10.1016/j.susmat.2024.e00832

[12] T. Toya, Y. Kameschina, A. Yasumori, and K. Okada, “Preparation and properties of glass-ceramics from wastes (Kira) of silica sand and kaolin clay refining,” *J. Eur. Ceram. Soc.*, vol. 24, no. 8, pp. 2367–2372, 2004. https://doi.org/10.1016/S0955-2219(03)00628-9

[13] C. Fu, J. Liang, G. Yang, A. A. Dagestani, W. Liu, X. Luo, B. Zeng, H. Wu, M. Huang, L. Lin, and X. Deng, “Recycling of waste glass as raw materials for the preparation of self-cleaning, light-weight and high-strength porous ceramics,” *J. Clean. Prod.*, vol. 317, p. 128395, 2021. https://doi.org/10.1016/j.jclepro.2021.128395

[14] J. M. Moreno-Maroto and J. J. Alonso-Azcárate, “What is clay? A new definition of “clay” based on plasticity and its impact on the most widespread soil classification systems,” *Appl. Clay Sci.*, vol. 161, pp. 57–63, 2018. https://doi.org/10.1016/j.clay.2018.04.011

[15] H. Celik, “Technological characterization and industrial application of two Turkish clays for the ceramic industry,” *Appl. Clay Sci.*, vol. 50, no. 2, pp. 245–254, 2010. https://doi.org/10.1016/j.clay.2010.08.005

[16] F. Hammami-Ben Zaied, R. Abidi, N. Slim-Shimi, and A. K. Somarin, “Potentiality of clay raw materials from Gram area (Northern Tunisia) in the ceramic industry,” *Appl. Clay Sci.*, vol. 112–113, pp. 1–9, 2015. https://doi.org/10.1016/j.clay.2015.03.027

[17] C. Mohmoudi, E. Srasra, and F. Zargouni, “The use of Tunisian Barremian clay in the traditional ceramic industry: Optimization of ceramic properties,” *Appl. Clay Sci.*, vol. 42, no. 1–2, pp. 125–129, 2008. https://doi.org/10.1016/j.clay.2007.12.008

[18] F. Andreola, C. Siligardi, T. Manfredini, and C. Carbonchi, “Rheological behaviour and mechanical properties of porcelain stoneware bodies containing Italian clay added with bentonites,” *Ceram. Int.*, vol. 35, no. 3, pp. 1159–1164, 2009. https://doi.org/10.1016/j.ceramint.2008.05.017

[19] M. Cargnin, S. M. A. G. Ulson de Souza, A. A. Ulson de Souza, and A. J. De Noni, “Modeling and simulation of the effect of the firing curve on the linear shrinkage of ceramic materials: Laboratory scale and industrial scale,” *Braz. J. Chem. Eng.*, vol. 32, no. 2, pp. 433–443, 2015. https://doi.org/10.1590/0104-6632.20150322s00002876

[20] S. L. Correia, K. A. S. Curto, D. Hotza, and A. M. Segadães, “Using experiments design to model linear firing shrinkage of triaxial ceramic bodies,” *Mater. Sci. Forum*, vol. 498–499, pp. 430–435, 2005. https://doi.org/10.4028/www.scientific.net/msf.498-499.430

[21] M. F. Nicolás, M. M. Chávez, M. Vlasova, and T. P. Puig, “Low-temperature sintering of ceramic bricks from clay, waste glass and sand,” *Bol. Soc. Esp. Cerám. Vidr.*, vol. 63, no. 5, pp. 377–388, 2024. https://doi.org/10.1016/j.bsecv.2024.06.003

[22] A. Casagrande, “Classification and identification of soils,” *Trans. Am. Soc. Civ. Eng.*, vol. 113, pp. 901–930, 1948. https://doi.org/10.1061/TACEAT.0006109

[23] ASTM, “ASTM D4318-10e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils,” ASTM International, 2010. https://store.astm.org/d4318-10e01.html

[24] ASTM, “ASTM D2487-11: Standard practice for classification of soils for engineering purposes (Unified Soil Classification System),” ASTM International, 2011. https://store.astm.org/d2487-11.html

[25] N. Yaghmaeiyan, M. Mirzaei, and R. Delghavi, “Montmorillonite clay: Introduction and evaluation of its applications in different organic syntheses as catalyst: A review,” *Results Chem.*, vol. 4, p. 100549, 2022. https://doi.org/10.1016/j.rechem.2022.100549

[26] C. Lascarro, F. Ochoa-Cornejo, V. Mercado, and J. Duque, “An extended hypoplastic model for sands with additions of highly plastic fines formulated under the ISA framework,” *Soil Dyn. Earthq. Eng.*, vol. 176, p. 108348, 2024. https://doi.org/10.1016/j.soildyn.2023.108348

[27] A. F. Chizhsky, *Sushka keramicheskikh materialov i izdelii*. Moscow: Stroyizdat, 1971.

[28] K. Ushimaru, A. Togo, N. Kamiuchi, R. Watanabe, K. Sakakibara, Y. Saito, A. Kumagai, S. Sato, and T. Fukuoka, “Nacre-inspired nanocomposites from natural polypeptide ε-poly-l-lysine and natural clay montmorillonite: Remarkable reinforcing effect at low polymer content and its mechanism,” *Biomacromolecules*, vol. 25, no. 11, pp. 7098–7107, 2024. https://doi.org/10.1021/acs.biomac.4c00451

[29] M. Escobedo and S. Mischler, “Dust and self-similarity for the Smoluchowski coagulation equation,” *Ann. Inst. Henri Poincaré C, Anal. Non Linéaire*, vol. 23, no. 3, pp. 331–362, 2006. https://doi.org/10.1016/j.anihpc.2005.05.001

[30] S. Wang, L. Gainey, J. Marinelli, B. Deer, X. Wang, I. D. R. Mackinnon, and Y. Xi, “Effects of vermiculite on in-situ thermal behaviour, microstructure, physical and mechanical properties of fired clay bricks,” *Constr. Build. Mater.*, vol. 316, p. 125828, 2022. https://doi.org/10.1016/j.conbuildmat.2021.125828

[31] T. K. Mukhopadhyay, S. Ghosh, S. Ghatak, and H. S. Maiti, “Effect of pyrophyllite on vitrification and on physical properties of triaxial porcelain,” *Ceram. Int.*, vol. 32, no. 8, pp. 871–876, 2006. https://doi.org/10.1016/j.ceramint.2005.07.002

[32] W. Widodo, S. Solihin, and S. Subari, “Effect of karangunggal bentonite addition on the mechanical strength of conventional ceramics,” *Indones. Min. J.*, vol. 22, no. 1, pp. 19–28, 2019. https://doi.org/10.30556/imj.Vol22.N

o1.2019.962

[33] O. Gencel, O. Kizinievic, M. Sutcu, E. Erdogmus, P. M. Velasco, D. Eliche-Quesada, V. Kizinievic, and H. Kurmus, “Effects of expanded vermiculite on the properties of fired bricks from water treatment sludge,” *Int. J. Appl. Ceram. Technol.*, vol. 19, no. 3, pp. 1214–1226, 2022. https://doi.org/10.1111/ijac.13979

[34] A. De Noni Junior, S. B. Canever, P. Henrique, and R. R. da Silva, “Microstructure-oriented porcelain stoneware tile composition design,” *Ceram. Int.*, vol. 49, no. 14, pp. 24 558–24 565, 2023. https://doi.org/10.1016/j.ceramint.2022.11.067

[35] E. M. Gikunju, G. O. Bosire, J. M. Onyari, F. W. Nyongesa, and D. Beleta, “Physico-chemical characterization of feldspars for application as fluxing agents: Experimental and ab initio computational approaches,” *Phys. Chem. Earth*, vol. 135, p. 103651, 2024. https://doi.org/10.1016/j.pce.2024.103651