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RESEARCH ARTICLE

THE USE OF MINERAL RAW MATERIALS OF ZHAMBYL REGION IN THE PRODUCTION OF BUILDING CERAMICS

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Abstract. *The utilization of clay raw materials in combination with industrial by-products, such as phosphorus slag and waste glass, offers an effective approach to expanding the raw material base of ceramic production, reducing environmental impacts, and improving the efficiency of natural resource utilization. This study evaluates the feasibility of using medium-plastic loam from the Sarykemer deposit, granulated phosphorus slag, and ground waste glass in the production of building ceramics and determines the optimal ceramic mass composition to achieve enhanced physical and mechanical properties. The chemical and mineralogical compositions of the raw materials and their influence on the properties of the ceramic body were investigated. Experimental specimens with different component proportions were prepared at a molding moisture content of 20%, followed by drying and firing at temperatures ranging from 900 to 1050 °C. The optimum firing temperature was determined based on the degree of sintering observed on the fracture surface and the physical and mechanical properties of the fired specimens. The optimal ceramic composition was found to consist of 80% loam, 15% phosphorus slag, and 5% ground waste glass. The incorporation of these additives enhanced the sintering process, promoted the formation of a dense ceramic body, and improved the physical and mechanical properties of the material. Specimens fired at the optimum temperature of 1000 °C exhibited a compressive strength of at least 20 MPa. The obtained results demonstrate the effectiveness of utilizing local mineral resources and industrial by-products from the Zhambyl region for the production of wall ceramics, enabling the manufacture of high-quality ceramic materials with improved performance, reduced consumption of natural raw materials, and enhanced environmental sustainability of the production process.*

Keywords: *phosphorus slag, glass fight, resource conservation, air shrinkage, density, strength, utilization of wastes.*

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ҒЫЛЫМИ МАҚАЛА

ҚҰРЫЛЫС КЕРАМИКАСЫН ӨНДІРУДЕ ЖАМБЫЛ ОБЛЫСЫНЫҢ МИНЕРАЛДЫ ШИКІЗАТЫН ПАЙДАЛАНУ

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Аңдатпа. *Саз шикізатын, фосфор қожы және әйнек сынығы тәрізді өнеркәсіптік қалдықтармен бірге пайдалану керамика өндірісінің шикізат базасын кеңейтуге, экологиялық жүктемені азайтуға және табиғи ресурстарды пайдалану тиімділігін арттыруға мүмкіндік береді. Жұмыста құрылыс керамикасын өндіру үшін "Сарыкемер" кен орнының илемділігі орташа саздағын, түйіршікті фосфор қожын және ұнтақталған әйнек сынықтарын қолдану мүмкіндігі бағаланды, сондай-ақ бұйымдардың жоғары физика-механикалық қасиеттерін қамтамасыз ететін керамикалық массаның оңтайлы құрамы анықталды. Бастапқы шикізаттың химиялық-минералогиялық құрамы және оның керамикалық массаның қасиеттеріне әсері зерттелді. 900-1050 °C температурада кептірілген және күйдірілген 20% қалыптау ылғалдылығында әртүрлі компоненттері бар үлгілер жасалды. Керамикалық массаның оңтайлы құрамына 80% саздақ, 15% фосфор қожы және 5% ұнтақталған әйнек сынығы кіретіні анықталды. Бұл қоспаларды енгізу жентектелу процестерін күшейтуге, керамикалық дененің тығыз құрылымын қалыптастыруға және материалдың физикалық-механикалық сипаттамаларын жақсартуға көмектеседі. Оңтайлы 1000 °C температурада күйдірілген үлгілер кем дегенде 20 МПа сығым беріктігімен сипатталады. Алынған нәтижелер жақсартылған пайдалану қасиеттері бар сапалы керамикалық материалдарды алуды, табиғи шикізат шығынын азайтуды және өндірістің экологиялылығын арттыруды қамтамасыз ете отырып, қабырға керамикасын өндіру үшін Жамбыл облысының жергілікті минералдық шикізаты мен өнеркәсіптік қалдықтарын пайдаланудың тиімділігін растайды.*

Түйін сөздер: *фосфор қождары, әйнек сынақтары, ресурстарды үнемдеу, ауалық шөгу, тығыздық, беріктік, қалдықтарды кәдеге жарату.*

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НАУЧНАЯ СТАТЬЯ

ИСПОЛЬЗОВАНИЕ МИНЕРАЛЬНОГО СЫРЬЯ ЖАМБЫЛСКОЙ ОБЛАСТИ В ПРОИЗВОДСТВЕ СТРОИТЕЛЬНОЙ КЕРАМИКИ

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Аннотация. *Использование глинистого сырья в сочетании с промышленными отходами, такими как фосфорный шлак и стеклобой, позволяет расширить сырьевую базу керамического производства, снизить экологическую нагрузку и повысить эффективность использования природных ресурсов. В работе оценена возможность применения среднепластичного суглинка месторождения «Сарыкемер», гранулированного фосфорного шлака и молотого стеклобоя для производства строительной керамики, а также определен оптимальный состав керамической массы, обеспечивающий высокие физико-механические свойства изделий. Исследованы химико-минералогический состав исходного сырья и его влияние на свойства керамической массы. Изготовлены опытные образцы с различным содержанием компонентов при формовочной влажности 20%, высушенные и обожженные при температурах 900–1050 °С. Оптимальную температуру обжига определяли по степени спекания в изломе образцов и показателям их физико-механических свойств. Установлено, что оптимальный состав керамической массы включает 80% суглинка, 15% фосфорного шлака и 5% молотого стеклобоя. Введение указанных добавок способствует интенсификации процессов спекания, формированию плотной структуры керамического черепка и улучшению физико-механических характеристик материала. Образцы, обожженные при оптимальной температуре 1000 °С, характеризуются прочностью на сжатие не менее 20 МПа. Полученные результаты подтверждают эффективность использования местного минерального сырья и промышленных отходов Жамбылской области для производства стеновой керамики, обеспечивая получение качественных керамических материалов с улучшенными эксплуатационными свойствами, снижение расхода природного сырья и повышение экологичности производства.*

Ключевые слова: *фосфорный шлак, бой стекла, ресурсосбережение, воздушная усадка, плотность, прочность, утилизация отходов.*

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1 INTRODUCTION

The modern development of the construction industry requires the expansion of the raw material base and the implementation of resource-saving technologies for manufacturing construction materials. One of the promising approaches involves the use of local mineral raw materials and technogenic additives for obtaining efficient ceramic materials with specified performance characteristics. Under conditions of increasing construction volumes, particular importance is attached to reducing production costs, rational utilization of natural resources, and minimizing environmental impact.

In recent years, significant attention has been focused on expanding the raw material base of the ceramic industry in Kazakhstan through the use of local clay resources and various modifying additives. Research has shown that the physicomechanical properties of ceramic materials can be controlled and optimized by introducing natural and industrial by-product components [1-5].

The Zhambyl Region possesses substantial reserves of mineral raw materials suitable for the production of building ceramics. Deposits of clays, loams, quartz sands, and other silicate-containing materials are widespread throughout the region and may serve as a basis for manufacturing ceramic bricks and wall products. At the same time, many types of local raw materials remain insufficiently studied with regard to their technological properties and the possibilities for their integrated use in ceramic production.

The use of regional raw material resources makes it possible to reduce transportation costs, improve the economic efficiency of production, and promote the development of local industry.

Additional interest is associated with the utilization of industrial mineral waste, which contributes to the rational use of natural resources and reduction of waste accumulation. Mineral waste also makes it possible to regulate the plasticity of molding bodies, reduce shrinkage, improve drying and firing processes, and form an optimal ceramic microstructure with enhanced strength characteristics while simultaneously reducing density and energy consumption during production.

Significant quantities of waste are generated during the production of phosphorus-containing products. One such waste material is phosphorus slag, which represents a large-tonnage by-product of the electrothermal phosphorus production process. In Kazakhstan, predominantly within the territory of the Zhambyl Region, enormous amounts of phosphorus industry waste have accumulated, amounting to tens of millions of tons. More than 10 million tons of phosphorus slag have been accumulated in the country [6,7].

The accumulation of phosphorus slag in waste dumps of the Zhambyl Region leads to the occupation of extensive land areas, environmental pollution, and deterioration of the ecological situation.

[8] presented averaged results of the chemical analysis of various phosphorus industry wastes from the Zhambyl Region. The main components were calcium and silicon oxides, while aluminum and iron oxides were also present in most waste materials. The presence of these oxides determines the hydration properties of raw materials used for the production of binding materials in construction and plays an important role in the technology of obtaining construction mixtures, including Portland cement, alumina cement, glass, fine ceramics, and other materials.

The results reported by [9] also demonstrate that the chemical composition of phosphorus slag mainly includes calcium oxide (CaO), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3), and that the material possesses a glassy structure with high thermal resistance. This allows phosphorus slag to be considered a promising raw material for manufacturing various types of construction materials.

Currently, practical experience exists regarding the use of phosphorus slag in the production of ceramic materials. Numerous researchers have demonstrated the effectiveness of phosphorus slag as an additive that reduces shrinkage, regulates firing temperature, and affects the structure formation processes of the ceramic body.

[10,11] demonstrated that the addition of phosphorus slag in amounts up to 20% promotes the crystallization of pseudowollastonite and larnite during brick firing, thereby providing a reinforcing

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effect, limiting drying and firing shrinkage, increasing the mechanical strength of ceramics, and significantly reducing the tendency of products to crack formation. Further increase in phosphorus slag content up to 30% reduces the plasticity of the ceramic body and, consequently, the binding capacity of the clay component, resulting in crack formation on the brick surface.

Phosphorus slag was also used for the production of wollastonite glass-ceramics [12]. It was established that the interaction between glass powder and graphite results in the formation of large pores with a uniform distribution during the production of foam glass-ceramics at a foaming temperature of 1000°C. In this case, porosity reached approximately 80%. The results demonstrated that wollastonite was the predominant crystalline phase, whereas the high compressive strength was attributed to glass crystallization during sintering.

Ceramic body compositions for the production of ceramic bricks were developed using phosphorus slag as a lean additive, ash-slag material containing more than 15% organic matter as a combustible additive and sintering intensifier. Ceramic brick with strength grade M200 was obtained at a firing temperature of 1050°C. It was noted that phosphorus slag can replace expensive natural wollastonite, which reduces the shrinkage of ceramic materials and promotes more uniform pore distribution within the specimen [13].

In studies conducted by researchers of M.Kh. Dulaty Taraz Regional University, a nanostructured composition based on phosphorus slag and bentonite clay used as a binder in an amount of 25% achieved a compressive strength of 27.1 MPa. With an increase in binder content from 25% to 40%, the sintering effect intensified, and the compressive strength of the specimens reached 54.3 MPa. The reported results indicate that the most intensive sintering and formation of dense structures in coarse-grained compositions containing high-calcium phosphorus slag occur at a binder content of 40–60%. The optimal technological parameters include a firing temperature of 1050-1100°C, pressing pressure of 20-25 MPa, and moisture content of the press powder of 7-8% [14]**.**

[15] used conventional ceramic technology for brick production. Ceramic specimens prepared from a plastic body with molding moisture content of 22–24% and an optimal raw material composition consisting of bentonite clay (50%), phosphorus slag (35%), and ash-slag mixture (15%), ground to pass through a 1 mm sieve, were fired at 1000°C. It was established that reducing the plasticity index from 25 to 8 while increasing the content of lean additives from 25% to 50% made it possible to obtain brick of strength grade M125, whereas the use of 25% lean additives resulted in brick of only grade M75.

One of the most difficult industrial wastes to utilize is waste glass. It is resistant to the effects of water and atmospheric factors such as precipitation, sunlight, and temperature fluctuations, and it is not decomposed by organic, mineral, or biologically active agents. The accumulation of such waste at glass manufacturing plants is relatively insignificant, since most defective products are returned to the melt as fluxing agents. However, the quantity of waste glass generated as consumer waste represents a serious environmental problem [16,17].

The utilization of waste glass and the investigation of physicomechanical properties of ceramic materials have been addressed in the works [18,19,20].

The reported research findings demonstrate that waste glass additives may be used as fluxing-strengthening components forming a glassy phase during firing and reducing the temperature of liquid-phase sintering, thereby enabling the production of ceramic materials with favorable physical, mechanical, and thermal properties. In turn, the glassy phase acts as a binder within the material volume owing to vitrification of ceramic particle surfaces and their integration into a durable framework.

Thus, an analysis of the published studies indicates that the use of phosphorus slag and waste glass in the production of building ceramics has been investigated mainly separately or in combination with other types of clay raw materials. However, there is a lack of systematic data on the feasibility of the integrated utilization of clay raw materials, phosphorus slag, and waste glass within a single ceramic composition, as well as on the effect of their combined application on

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sintering processes, shrinkage behavior, and strength characteristics of building ceramics. In addition, the optimal proportions of these components and firing regimes required to obtain products with the desired performance properties remain insufficiently studied.

The scientific novelty of this work lies in the experimental substantiation of the possibility of the integrated utilization of local loam from the Sarykemer deposit, granulated phosphorus slag, and waste glass for the production of building ceramics with improved physicomechanical properties. For the first time, rational ceramic body compositions and technological production parameters have been determined for the investigated raw material system, ensuring the formation of a dense ceramic microstructure at a firing temperature of 1000 °C. It was established that the incorporation of 15 wt.% phosphorus slag and 5 wt.% waste glass reduces drying shrinkage to 0.6%, intensifies sintering processes, and provides a compressive strength exceeding 20 MPa. New data were obtained on the combined effect of phosphorus slag and waste glass on the structure formation and properties of ceramic materials based on raw materials from the Zhambyl region.

The practical significance of the work lies in the development of a ceramic body composition suitable for the production of wall ceramic materials using local mineral resources and industrial waste generated in the region. The proposed solution makes it possible to expand the raw material base of ceramic manufacturing enterprises, reduce the consumption of natural resources, and promote the utilization of large-tonnage phosphorus industry waste and waste glass. The results of the study can be applied in the development of resource-efficient technologies for the production of ceramic bricks and other wall products at industrial enterprises in Kazakhstan.

2 MATERIALS AND METHODS

As the main raw material for obtaining construction ceramics, loams from the "Sarykemer" (formerly Mikhaylovskoye) deposit located in the Zhambyl region were used, while granulated phosphorus slag (GPS) from the "Kazphosphate" plant, also located in the Zhambyl region, was used as a thinning additive. The "Sarykemer" deposit is represented by a bedded loam formation with a plasticity index of 7-12.4 (average value 8.5). The main clay component of the loam is up to 12% montmorillonite occurring in the form of mixed-layer formations with hydromica and kaolinite, which was confirmed by thermal analysis of the loam performed using a Q-1500D derivatograph. During heating of the loam, endothermic effects were recorded on the DTA curve at 140, 560, and 860 °C, corresponding to the removal of adsorption, interlayer, and constitutional water of clay minerals (Figure 1).

A pronounced endothermic effect associated with the removal of absorbed water was observed at 140 °C, while the step detected on the curve at 220 °C indicates the removal of interpacket water. The second effect (550-580 °C) corresponds to the removal of constitutional water (bound in the form of OH groups), which is characteristic of montmorillonite. The layered structure remains stable up to temperatures above 800 °C.

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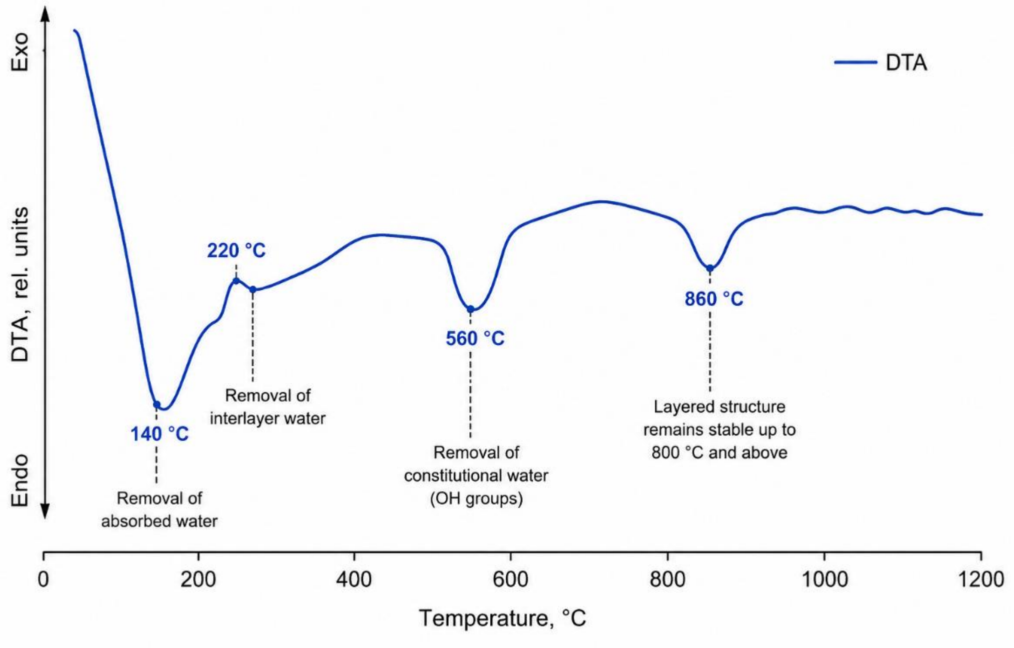

Figure 1 – Thermogram of loam from the "Sarykemer" deposit [Authors' material]

The components were selected taking into account their chemical and mineralogical composition (Tables 1 and 2), plasticity, and influence on the forming and firing processes.

Table 1 - Mineralogical composition of loam [Authors' material]

Clay minerals	Quartz	Feldspar	Carbonates	Iron oxides
25-30	5-10	45	5-10	5

Table 2 - Chemical composition of loam and phosphorus slag [Authors' material]

Raw material name	Oxide content, wt.%										
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_3	MnO_2	Na_2O	P_2O_5	F
"Sarykemer" loam	52.91	11.51	4.45	0.55	10.48	2.86	0.25	0.93	-	0.18	-
Phosphorus slag	42.5	3.1	0.4	-	45.4	2.1	0.6	-	0.67	1.5	1.0

The chemical (oxide) composition of the mineral raw materials was determined using X-ray fluorescence analysis (XRF). The particle size distribution of the raw materials was determined by sieve analysis (Table 3, 4).

The phase composition of phosphorus slag is represented by glass of the pseudowollastonite mineral. The average density was – 1100-1200 kg/m^3.

The microstructure of the ceramic specimens was investigated using scanning electron microscopy (SEM).

Table 3 - Particle size distribution of loam [Authors' material]

Fraction, mm	0.5-0.01	0.01-0.001	Less than 0.001	More than 0.5
Content, %	66.85	22.05	11.4	7.23

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Quartz sand and waste glass were used to adjust the composition of the ceramic body. In the Zhambyl Region, waste glass (cullet and glass containers) is collected by specialized recycling centers mainly located in Taraz and district centers, including the village of Sarykemer. Waste glass recycling makes it possible to process the material into new glass containers or building materials.

The clay raw material was preliminarily dried to an air-dry condition and crushed followed by sieving through a 2.5 mm mesh sieve. Phosphorus slag, quartz sand, and waste glass were ground and sieved to a particle size below 1 mm.

The components were dosed by weight and thoroughly mixed until a homogeneous body was obtained. After dry mixing, water was gradually added to the mixture until the required molding moisture content was achieved. Specimens in the form of cubes measuring 2×2×2 cm and cylindrical specimens measuring 5×5 cm were produced from the prepared ceramic body by the plastic molding method. Molding was carried out manually.

The molded specimens were dried in a drying oven at a temperature of 105 ± 5°C until constant weight was achieved. During drying, changes in specimen weight, air shrinkage, and drying sensitivity coefficient were determined. The dried specimens were fired in a laboratory muffle furnace. Firing was carried out at temperatures of 900, 950, 1000, and 1050°C. Holding time at the maximum temperature was 45–60 min for specimens measuring 2×2×2 cm and 1–2 h for cylindrical specimens measuring 5×5 cm. The optimal firing temperature and holding time were determined based on the uniformity of sintering observed in the fracture surface of the products and the physicomechanical properties of the final ceramic material.

After completion of firing, the specimens were cooled inside the furnace to room temperature.

The compressive strength of ceramic specimens was determined by uniaxial compression testing using a hydraulic press. The tests were carried out in accordance with the requirements of current standards for wall ceramics.

The determination of clay plasticity and drying properties of the specimens, including air shrinkage and drying sensitivity, was performed in accordance with GOST 21216-2014 “Clay Raw Materials. Testing Methods”. Air shrinkage was determined by measuring the linear dimensions of plate specimens measuring 100×100×10 mm after molding and after drying. Drying sensitivity was determined on identical specimens using the accelerated Chizhsky method.

All experimental studies were conducted on at least three parallel specimens. The obtained results were averaged, after which relationships between specimen properties, ceramic body composition, and firing temperature were established.

3 RESULTS AND DISCUSSION

Based on the conducted investigations, the possibility of using mineral raw materials from the Zhambyl Region for the production of building ceramics with improved performance characteristics was evaluated.

In order to obtain high-quality ceramic products based on clays of various chemical and mineralogical compositions, it is desirable that the ceramic body composition ensures the formation of a sufficient amount of liquid phase. One of the approaches to achieving a sufficient liquid phase content consists in introducing fluxing agents into the ceramic body.

In the present study, phosphorus slag containing a significant amount of silica oxides also acted as a fluxing component reducing the firing temperature of ceramic products.

Initially, experimental ceramic body compositions with phosphorus slag content varying from 0 to 15% were tested.

The conducted investigations demonstrated that the incorporation of phosphorus slag into ceramic body compositions promotes the production of high-strength ceramic brick with compressive strength reaching 26.3 MPa. The optimal composition was determined to contain 85 wt.% loam and 15 wt.% phosphorus slag. A significant decrease in air shrinkage was observed with increasing

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phosphorus slag content, from 5.8% for pure loam to 0.5%. The optimal firing temperature was established as 1000°C, ensuring high strength characteristics.

Molding moisture content exerts a certain influence on both technological processes and the properties of the semi-finished product. In this regard, investigation of the green strength of the semi-finished product as a function of moisture content made it possible to determine the optimal molding moisture content for the batch corresponding to the optimal composition (loam:phosphorus slag = 85:15), which should not exceed 21.3%. Variation in compressive strength depending on the composition of the "loam–phosphorus slag" ceramic body is shown in Figure 2.

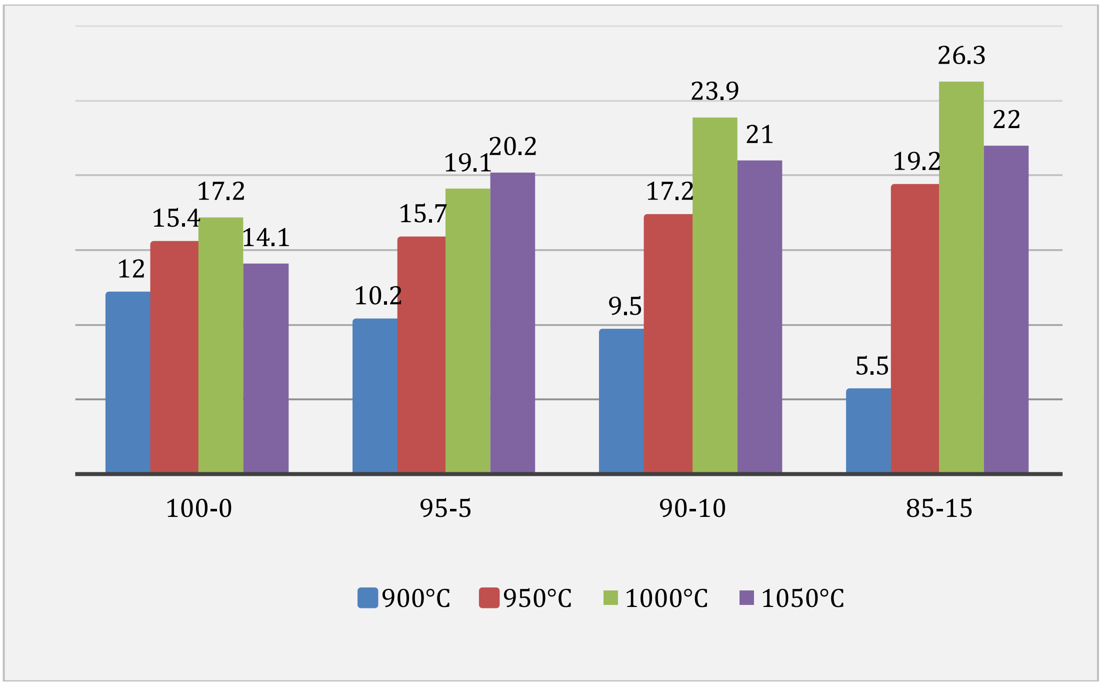

Figure 2 – Variation of compressive strength depending on the composition of the "loam–phosphorus slag" ceramic body [Authors' material]

In order to reduce energy consumption and firing temperature, compositions containing finely ground waste glass and quartz sand were also investigated. However, the addition of sand to the mixture did not provide the desired results (Table 5).

Table 5 - Physicomechanical properties of ceramic specimens based on the clay–phosphorus slag–sand composition at different ratios [Authors' material]

Composition No.	Component ratio, clay:phosphorus slag:sand, %	Drying sensitivity, min	Molding moisture content (absolute), %	Air shrinkage, %	Average green density, g/cm³	Properties of specimens fired at 1000°C; Compressive strength, water absorption, and average density		
						R_{cs}, MPa	W, %	ρ, g/cm³
1	80:15:5	0.31	19.25	0.4	1.74	6.25	16.4	1.70
2	78:15:7	0.23	18.00	0.3	1.49	4.46	15.2	1.6

As a result of analyzing changes in the physicomechanical properties of ceramic compositions within the "composition–temperature" system, optimal ratios of the constituent components were identified, at which minimum firing shrinkage and bulk density values, as well as maximum strength characteristics, were achieved. At the same time, water absorption satisfied standard requirements.

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These conditions correspond to compositions with the following limiting concentrations of the constituent components: loam 85-80% and phosphorus slag 10-15%.

The optimal firing temperature when using waste glass was 1000°C, at which the compressive strength of the products reached 21.39 MPa. The addition of 5% finely ground waste glass made it possible to obtain specimens retaining their original color while maintaining high strength characteristics. Air shrinkage and drying sensitivity changed insignificantly; however, the compressive strength of the specimens decreased compared with compositions containing only clay and slag. Nevertheless, waste glass may be used for additional reduction of firing temperature, i.e., as a fluxing additive, as well as for waste utilization purposes. The results are presented in Table 6.

Table 6 - Physicomechanical properties of ceramic specimens based on the clay–slag–glass composition at different ratios [Authors' material]

Composition No.	Component ratio, clay:slag:glass, %	Drying sensitivity, min	Molding moisture content (absolute), %	Air shrinkage, %	Average green density, g/cm³	Properties of specimens at firing temperature: compressive strength, water absorption, and average density					
						900°C			1000°C		
						R_{cs}, MPa	W, %	ρ, g/cm³	R_{cs}, MPa	W, %	ρ, g/cm³
1	87:10:3	0.52	19.4	0.7	1.77	9	16.4	1.52	19.07	15.2	1.60
2	82:15:3	0.27	18.8	0.5	1.71	15.98	18.1	1.60	18.6	15.9	1.6
3	85:10:5	0.61	20.5	0.9	1.9	7.73	17.1	1.61	20.09	16.1	1.67
4	80:15:5	0.36	20.0	0.6	1.85	15.4	18.7	1.58	21.4	17.2	1.74
5	83:10:7	0.40	18.3	0.6	1.54	11.08	16.9	1.59	15.98	17.1	1.73
6	78:15:7	0.22	18	0.4	1.59	12.36	17.2	1.42	16.74	16.5	1.62

The increase in the strength of the ceramic material with the addition of phosphorus slag is attributed to its high content of calcium and silicon oxides. At firing temperatures of approximately 1000 °C, these oxides participate in the formation of a liquid phase, which enhances the sintering process and increases the density of the ceramic body. Waste glass acts as a flux due to its relatively low softening temperature. During firing, the glass particles partially soften and melt, resulting in the formation of a glassy phase. This glassy phase reduces the open porosity and promotes the development of a denser microstructure. The combined use of phosphorus slag and waste glass produces a synergistic effect through the simultaneous formation of a liquid phase and enhanced mass transport during sintering. As a result, a denser ceramic matrix with improved interparticle bonding is formed, which is confirmed by the microstructural observations obtained using scanning electron microscopy (SEM).

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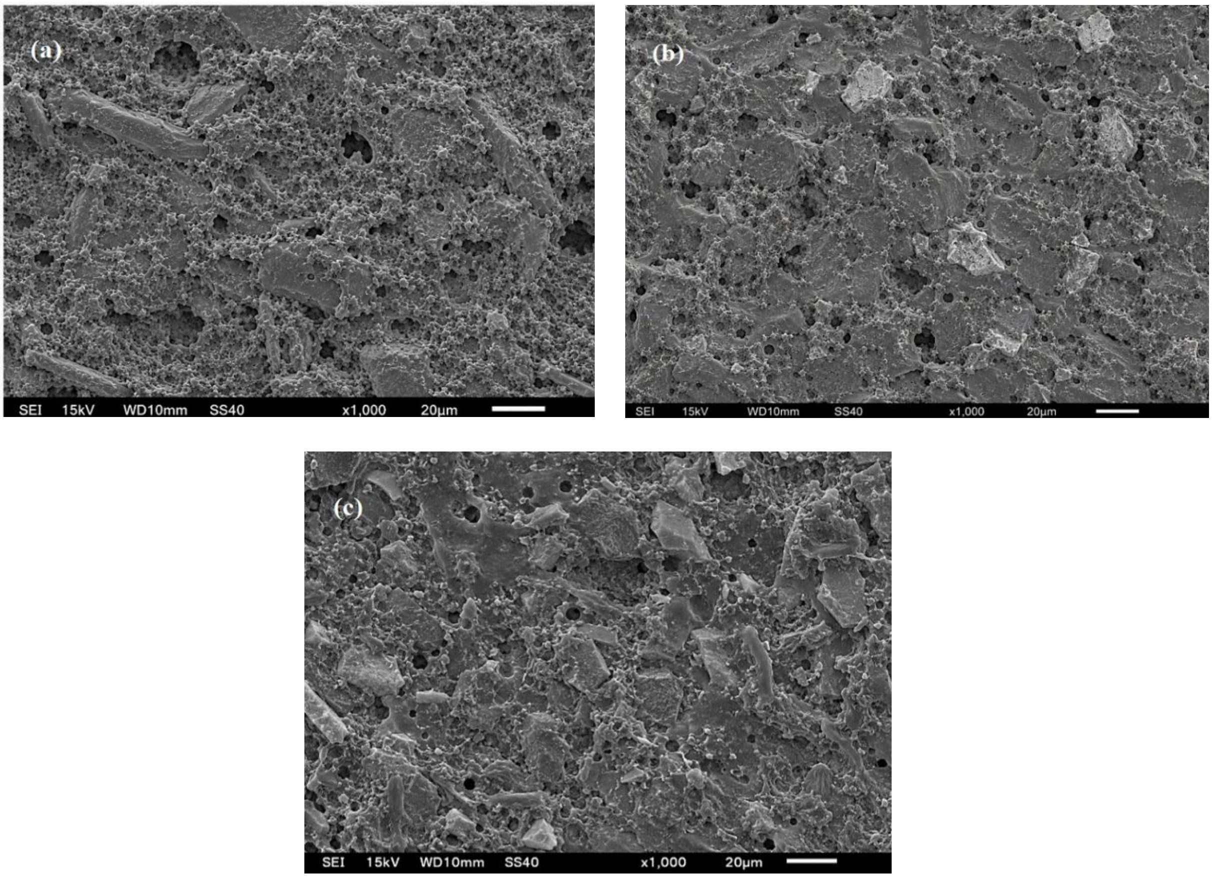

Figure 3 – SEM micrographs of ceramic specimens with different compositions (magnification ×1000; scale bar: 20 μm): (a) 100% loam; (b) 85% loam + 15% phosphorus slag; (c) 80% loam + 15% phosphorus slag + 5% waste glass. [Authors' material]

The microstructure of the control specimen prepared solely from loam without mineral modifying additives (Figure 3a) is characterized by a heterogeneous ceramic matrix with pronounced open porosity. The surface consists of aggregates of sintered clay particles separated by intergranular voids and pores of predominantly rounded and irregular shapes, ranging in size from approximately 2 to 20 μm. The interparticle contacts are not fully developed, indicating a relatively low degree of sintering. The glassy phase is virtually absent, resulting in a rougher microstructure and a less densely packed ceramic matrix.

Compared with the control specimen, the incorporation of 15% phosphorus slag leads to the formation of a denser and more homogeneous ceramic matrix (Figure 3b). The microstructure contains bright angular inclusions corresponding to phosphorus slag particles, which are uniformly distributed throughout the material. More developed interparticle contacts are observed, while localized glassy regions contribute to particle bonding and structural densification. The pores are predominantly irregular in shape and more uniformly distributed, whereas both their number and size decrease due to the enhanced sintering process. These microstructural features indicate that phosphorus slag promotes the formation of a denser ceramic structure with improved interparticle bonding.

The SEM micrograph of the ceramic specimen containing 80% loam, 15% phosphorus slag, and 5% waste glass (Figure 3c) demonstrates effective densification while maintaining limited open porosity. The dense heterogeneous ceramic matrix is mainly formed by loam particles. A partially melted glassy phase, generated from the melting of waste glass during firing, is observed between the grains, promoting particle bonding and increasing the overall density of the structure. Rounded and elongated pores, approximately 2–20 μm in size, are uniformly distributed throughout the material. Bright angular inclusions correspond to phosphorus slag particles, exhibiting enhanced contrast due to differences in the average atomic number. The glassy phase filling the intergranular space provides

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strong interparticle bonding, whereas the residual porosity indicates that the sintering process has not been completed entirely. The observed microstructure is characteristic of ceramic materials containing both a glass-forming additive and a mineral modifier and demonstrates the beneficial effect of waste glass on the densification of the ceramic body.

The results of the visual examination of ceramic specimens with different compositions after firing at 1000 °C (Figure 4) are consistent with the SEM observations. The control specimen exhibits a heterogeneous porous structure with relatively large open pores. The addition of phosphorus slag reduces the porosity and promotes the formation of a denser ceramic body. The combined incorporation of phosphorus slag and waste glass further enhances the sintering process, resulting in a more compact microstructure, which is indirectly confirmed by the increased mechanical strength and reduced water absorption of the ceramic specimens.

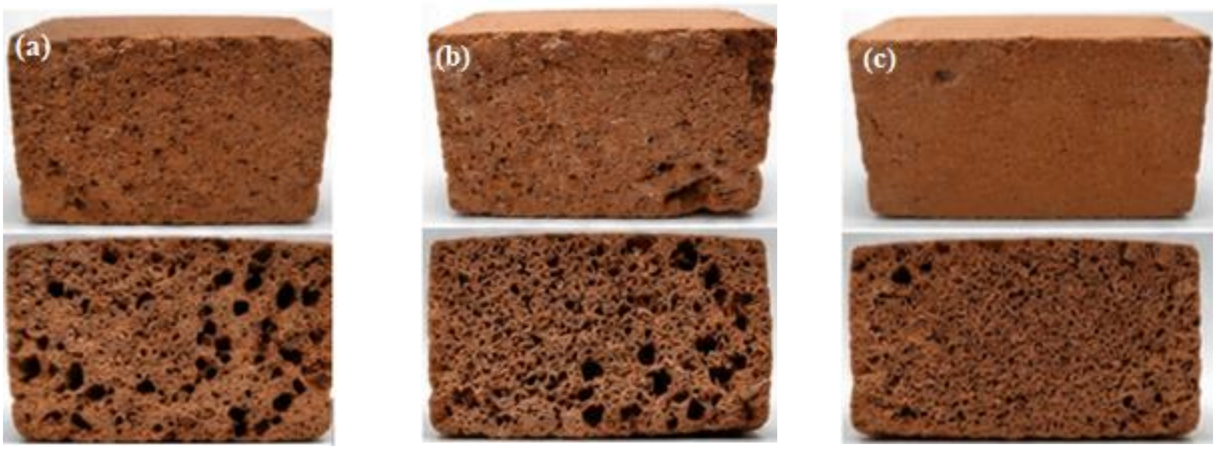

Figure 4 – Ceramic samples of various compositions after firing ((a) 100% loam), (b) 85% loam + 15% phosphorus slag, (c) 80% loam + 15% phosphorus slag + 5% glass cullet) [Authors' material]

Table 7 - Comparison of Physicomechanical Properties with the Requirements of GOST 530–2012 [Authors' material]

Property	Obtained Values	Requirements for Ceramic Brick According to GOST 530–2012
Compressive strength	18,6-21,4 MPa	Not less than 15 MPa
Water absorption	15,2-17,2 %	6-20 %
Bulk density	1,60-1,74 g/cm³	Corresponds to conditionally efficient wall ceramics

As shown in Table 7, the obtained compressive strength values (up to 21.4 MPa) comply with the requirements for M150–M200 grade wall ceramics according to GOST 530–2012. The obtained results are consistent with the findings of Montayev et al. [3], who reported a positive effect of mineral corrective additives on sintering processes and the formation of the ceramic body structure. Similar trends have also been observed when using ash-and-slag waste in ceramic compositions [4].

Compared with the results reported by Suleimenov [14], where compressive strength values of 27.1–54.3 MPa were achieved through the use of high concentrations of phosphorus slag and pressure molding, the developed compositions are characterized by a simpler manufacturing process and a lower firing temperature. The obtained results are also consistent with findings reported by other researchers, who have noted the beneficial effects of phosphorus slag and waste glass on sintering processes and the enhancement of the mechanical strength of ceramic materials.

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4 CONCLUSIONS

The possibility of using mineral raw materials from the Zhambyl Region for the production of building ceramics was investigated, and the influence of ceramic body composition on the physicomechanical properties of the obtained products was studied.

1. The loam from the «Sarykemer» deposit may be used as the principal clay component for the production of ceramic products owing to its physicomechanical properties.

2. The montmorillonite content in the loam promotes brick sintering processes at firing temperatures of 1000–1050°C.

3. Phosphorus slag may replace expensive natural wollastonite, which reduces the shrinkage of ceramic materials and, consequently, decreases product deformation.

4. The optimal compositions for ceramic brick production are the following, wt.%: loam – 85, phosphorus slag – 15; and loam – 80, phosphorus slag – 15, waste glass – 5.

5. The introduction of phosphorus slag into ceramic body compositions significantly improves the physicomechanical properties of brick at a firing temperature of 1000°C (26.3 MPa), reduces shrinkage, and decreases the probability of crack formation.

6. The addition of 5% finely ground waste glass makes it possible to obtain specimens retaining their original color while maintaining high compressive strength values (Rc = 21.39 MPa) at a firing temperature of 1000°C. Excessive amounts of waste glass may cause deformation of products during firing.

7. The introduction of phosphorus slag and glass cullet contributes to the formation of a denser and more homogeneous structure of the ceramic material, reducing the number of defects due to the formation of a glassy phase, which positively affects the physical and mechanical properties of ceramics.

8. Phosphorus slag and waste glass may be used both for reducing firing temperature, i.e., as fluxing additives, and for addressing environmental problems associated with waste utilization.

9. The developed composition can be recommended for the production of wall ceramic materials at relatively low firing temperatures (950-1000 °C).

10. Future research will focus on evaluating the influence of the particle size distribution of the batch components on the microstructure and performance characteristics of the ceramic materials. Particular attention will be paid to frost resistance testing, which is considered one of the key indicators of the long-term durability of structural ceramic products.

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The authors state that there is no conflict of interest.

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