Technobius, 2025, 5(3), 0086, DOI: https://doi.org/10.54355/tbus/5.3.2025.0086

Technobius

https://technobius.kz/

e-ISSN 2789-7338

Article

The influence of opoka mineral additive on the physico-mechanical properties of gas-ceramics based on low-plasticity clay

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Abstract. The article presents the results of scientific and experimental research on the development of highly porous gas-ceramics based on low-plasticity clay from the Rubezhinsk deposit. As a mineral additive, highly dispersed microporous siliceous rock-opoka from the Taskala deposit was used. Opoka is a lightweight, hard, microporous rock characterized by high natural porosity (55-60%) and a density of 1.3-1.5 g/cm³. Hydrogen peroxide, chemically composed of H_2O_2 (perhydrol), was employed as the foaming agent. The raw clay material contains 68% SiO_2, 11.8% Al_2O_3, 3.6% Fe_2O_3, and 5.6% CaO, and is classified as low-plasticity with a plasticity index of 6.5%. X-ray diffraction analysis revealed that the clay is predominantly composed of quartz, feldspar, calcite, and hematite, while the opoka consists primarily of amorphous silica. Experimental studies demonstrated that introducing 10-30% finely ground opoka into the clay slip reduces sedimentation of molded samples during drying from 12% (without additive) to 4% (at 30% opoka), thereby decreasing shrinkage and accelerating structural strength development by 10-15%. The resulting gas-ceramic samples exhibited average densities ranging from 565 to 785 kg/m³, compressive strength between 2.5 and 3.8 MPa, total porosity from 68.4% to 75.2%, and thermal conductivity values of 0.18–0.24 W/m·°C. These results indicate that the use of siliceous opoka significantly improves the performance characteristics of porous ceramics. Thus, the developed gas-ceramic materials combine low density, enhanced strength, and low thermal conductivity, making them suitable for use as effective structural-thermal insulation components in building envelope systems, particularly for the northern regions of Kazakhstan.

Keywords: low-plasticity clay, siliceous rock (opoka), gas-ceramics, foaming agent, bulk density, compressive strength, thermal conductivity coefficient, thermal insulation.

1. Introduction

The expansion of the product range and the increase in the production of thermal insulation and structural-thermal insulation products based on mineral raw materials is a relevant and pressing task, particularly for the northern regions of Kazakhstan. The demand of the construction sector for such materials can be partially met by developing new compositions and technologies for manufacturing individual units made of porous construction ceramics. This conclusion is supported by the availability, regional distribution, and the technical and economic accessibility of clay-based raw materials in Kazakhstan.

The creation of a highly porous structure in ceramic materials can be achieved during the preparation of the mass and the forming of the products, followed by structural fixation through firing. However, the high-temperature method of porosifying ceramic masses is more fuel- and energy-intensive and technologically complex compared to the method of porosifying clay slip. The latter approach requires scientific and technological justification, taking into account the specific mineralogical characteristics of the clay raw materials used.

This necessitates the development of construction materials science technologies aimed at increasing the production volume of cost-effective structural and thermal insulation products based on locally available mineral raw materials. Ceramic construction materials are known for a number of valuable technical properties, including durability, chemical and fire resistance, strength, environmental friendliness, and fire safety. In this regard, lightweight and cellular composites based on ceramic matrices can be considered promising materials with significant potential to improve thermal, mechanical, and other critical performance characteristics.

This approach is quite common in global practice. The study [1] examines the stabilization of silty clay in seasonally frozen regions using lime, ground granulated blast furnace slag (GGBS), and fly ash (FA) as curing agents. Laboratory tests, including UCS, freeze–thaw cycles, SEM, and XRD, identified an optimal LGF mixture ratio of 4:14:6 (lime:GGBS:FA) with 18% content, which enhanced strength through the formation of C–S–H and C–A–H compounds. A database of 270 UCS results was used to train machine learning models, where the PSO–BP model achieved the highest predictive accuracy ($R^2 = 0.982$). Analyses showed LGF and silty clay contents as the most critical factors. The research combines microstructural insights with machine learning to develop a reliable model for predicting soil strength under freeze–thaw conditions, offering practical guidance for geotechnical applications [1]. Another authors [2] investigates the use of sepiolite (SEP), a natural fibrous clay mineral, as an internal curing additive in cement pastes. Adding 2.5% SEP, particularly in the pre-absorbent state, was found to improve cement hydration, refine pore structure, and significantly enhance strength – compressive strength by 18.08% and flexural strength by 51.35%. Pre-absorbent SEP showed better dispersibility, enabling fiber reinforcement, pozzolanic activity, nucleation, and filling effects, while also providing internal curing. These improvements led to lower porosity, higher hydration degree, and increased C–S–H content, ultimately boosting both micro- and macroscopic performance. The findings highlight SEP's potential to sustainably enhance cement-based materials [2]. The paper [3] evaluates the use of sargassum ash as a mineral additive in ceramic clays to reduce raw material consumption and provide a sustainable use for stranded sargassum. Ceramic specimens with 10% and 20% ash were sintered at 800, 900, and 1000 °C and tested for physical and mechanical properties. The best results were obtained with 10% sargassum ash at 900 °C and 1000 °C, showing improved mechanical performance. A Life Cycle Assessment revealed that sintering is the main source of environmental impact, but incorporating 10% sargassum ash at 900 °C can both lower environmental impacts and enhance material performance compared to conventional ceramic clay [3]. The paper [4] explores the use of biomass ash, a byproduct of renewable energy generation, as the sole additive for stabilizing purple soil under different curing conditions. High-temperature treatment at 800 °C enabled the ash to consistently improve soil strength, with unconfined compressive strength (UCS) varying by curing environment. Under dry conditions, strength gains were linked to cementing effects from soluble salts and calcite, while under humid conditions, they were driven by mineral damage, particle contact changes, and multi-component cementation. The findings show that 800 °C-treated biomass ash can effectively reinforce purple soil, reduce water loss, and provide an environmentally sustainable method for waste ash utilization and soil stabilization [4]. The study [5] examines how Ground Granulated Blast-furnace Slag (GGBS), lime, and fly ash interact to improve the strength of gypsum soil. Soil mixtures with up to 16% additives were cured for different periods and tested. Results showed that fly ash alone did not significantly increase uniaxial compressive strength (UCS) but accelerated pozzolanic reactions. The greatest strength gain occurred at 28 days, driven by ettringite and silica gel formation, while earlier gains were due to cation exchange and flocculation. Microstructural analysis confirmed the growth of cementitious compounds (CH, CSHH, CHS, CAH, CASH) and ettringite crystals, which initially enhanced strength but later caused reductions in UCS at 56 days due to excessive crystal growth. Elemental analysis revealed shifts in Al:Si and Ca:Si ratios, with a marked Al:Si reduction at 28 days, indicating rapid cementitious compound formation. Overall, the findings highlight the complex role of curing time and additive interactions in strengthening gypsum soil [5]. [6] explores the partial replacement of Portland cement (PC) with bentonite clay (BC) to develop more sustainable concrete. Mortar samples were prepared with up to 30% BC, alongside artificial aggregates produced from ground granulated blast furnace slag (GGBFS) and PC. After 28 days, tests showed that samples with 5% BC achieved nearly double the compressive strength (94.7% higher) and a 31.2% reduction in thermal conductivity compared to the control. However, BC levels above 15% led to a decline in both strength and thermal performance. The findings demonstrate that limited substitution of cement with natural bentonite can enhance mechanical and thermal properties while supporting sustainable construction practices [6]. [7] investigates the reuse of kaolin excavation waste—typically nine tons per ton of kaolin recovered – by solidifying it with quicklime (CaO), reactive magnesia (MgO), and sodium carbonate under early-age oven curing. Strength development was analyzed through mechanical testing, pH, porosity, FTIR, XRD, and SEM-EDX, alongside environmental impact assessments of the additives. Results showed that both CaO and MgO improved compressive strength, with MgO performing better (20.3 MPa vs. 12.2 MPa at 28 days). MgO's advantage, especially with oven curing, was linked to the formation of fibrous nesquehonite crystals and fewer micro-cracks. The findings highlight MgO as a more sustainable and effective alternative to CaO and Portland cement for clay solidification, making it a promising option for environmentally friendly construction materials.

An analysis of patent literature and previous research findings indicates the presence of positive international experience in the use of natural siliceous materials in porous ceramic technologies designed to improve the indoor microclimate in residential buildings. The challenge of improving the quality and affordability of fired cellular materials can be addressed by incorporating unconventional ceramic raw materials derived from local rock formations.

One such resource is the natural siliceous rock known as opoka from the Western Kazakhstan deposit. This study focuses on the development of effective structural-thermal insulating gas-ceramic materials produced from the most accessible low-plasticity clays and siliceous rocks – opoka.

Gas-ceramic materials are renowned for their exceptional mechanical strength and corrosion resistance, offering a wide range of applications across various industries. Moreover, the porous structure plays a crucial role in determining the properties of foamed materials. Since air has a low thermal conductivity of 0.026 W/(m·K) at 25°C – especially when compared to multicomponent glass, which ranges from 0.771 to 0.971 W/(m·K) [8], [9] – the incorporation of pores into the material matrix can significantly reduce overall thermal conductivity.

In addition, closed pores help suppress thermal radiation and convection, leading to optimized effective thermal conductivity under non-vacuum conditions. Beyond thermal benefits, closed pores also contribute to enhanced mechanical strength and reduced water absorption [10], [11], [12], [13], [14], making these materials an excellent choice for a variety of applications.

2. Methods

At the initial stage of the study, an assessment was conducted on the properties of raw materials intended for the production of ceramic products with a highly porous structure.

The object of the study was low-plasticity clay from the Rubezhinsk deposit, located in the West Kazakhstan Region (WKR).

The chemical composition of the clay raw material was determined in accordance with GOST 2642.0-81 and GOST 2642.12-81 (Table 1).

Table 1 – Chemical composition of clay from the Rubezhinsk deposit, WKR

Raw Material Name	Oxide Content, wt.% (or fully: Oxide Content, % by mass)								
	SiO2	AL2O3	Fe2O3	CaO	MgO	Na2O	K2O	SO3	etc
Clay Raw Material from the Rubezhinsk Deposit	68	11.8	3.6	5.6	1.6	1.5	2.22	-	4.8

The determination of the granulometric composition and plasticity of the clay was carried out in accordance with GOST 21216.2-93 "Clay Raw Materials. Methods of Analysis" and GOST 9169-75 "Clay Raw Materials for the Ceramic Industry. Classification" (Tables 2 and 3).

Table 2 – Granulometric composition of clay from the Rubezhinsk deposit, WKR

Raw material name	Clay particle content	Silt particle content	Sand particle content	Type of clay raw material
Clay from Rubezhinsk deposit	13.62	70.78	15.6	Dusty loam, medium-dispersed

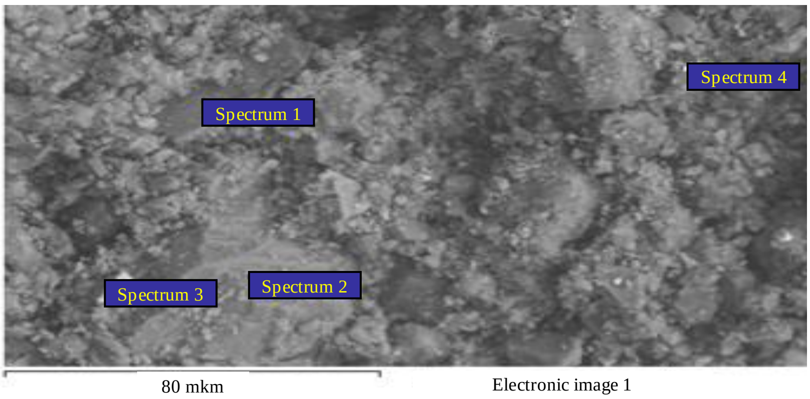
Table 3 – Plasticity of clay from the Rubezhinsk deposit, WKR

Raw material	Plasticity limits		Plasticity index, %	Classification of clay raw material by plasticity index
	Lower liquid limit	Upper rolling limit		
Clay from Rubezhinsk deposit	22.92	16.42	6.5	Low-plasticity

The drying sensitivity coefficient of the clay was determined using a rapid method proposed by A. F. Chizhsky. This device is based on measuring the time it takes for cracks to appear on the surface of a wet clay sample when exposed to intense thermal radiation. The method is characterized by its speed and the simplicity of the apparatus design. It was found that the time required for the first cracks to appear in the studied clay was 50–60 seconds, which classifies it as highly sensitive to drying.

The determination of chemical elements was carried out using a JSM 6490LV INCA Energy-350 scanning electron microscope (OXFORD Instruments, UK) by JEOL (Japan), equipped with an HKL Basis energy-dispersive analysis system (OXFORD Instruments, UK), suitable for working with polycrystalline materials (Figure 1).

Element	Weight %	Atomic %
C	7.99	12.92
O	50.94	61.83
Na	0.64	0.54
Mg	1.41	1.13
Al	5.47	3.94
Si	19.40	13.42
K	1.66	0.82
Ca	7.58	3.67
Ti	0.28	0.11
Mn	0.08	0.03
Fe	4.54	1.58



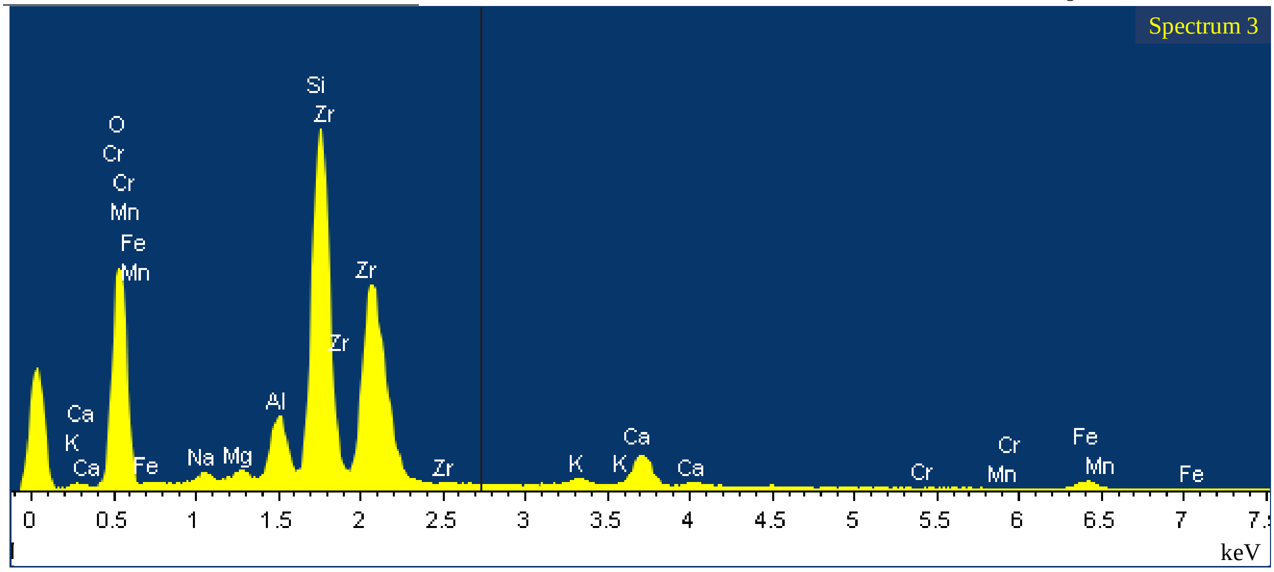


Figure 1 – Results of chemical analysis using SEM with INCA energy microanalysis system of low-plasticity clay from the Rubezhinsk deposit

The qualitative mineralogical composition of the clay was determined using the X-ray phase analysis (XRD) method on a DRON-3 diffractometer with CuKα radiation, within the angle range of 8° to 64°. The sensitivity of the method ranges from 1% to 2%. Powdered samples that passed through a 0.315 mm sieve were subjected to X-ray phase analysis. The identification of the diffraction patterns was performed using reference data [15] (Figure 2).

The interpretation of the X-ray diffraction patterns was carried out using an X-ray diffraction ruler and X-ray mineralogical identification methods based on the handbook [16].

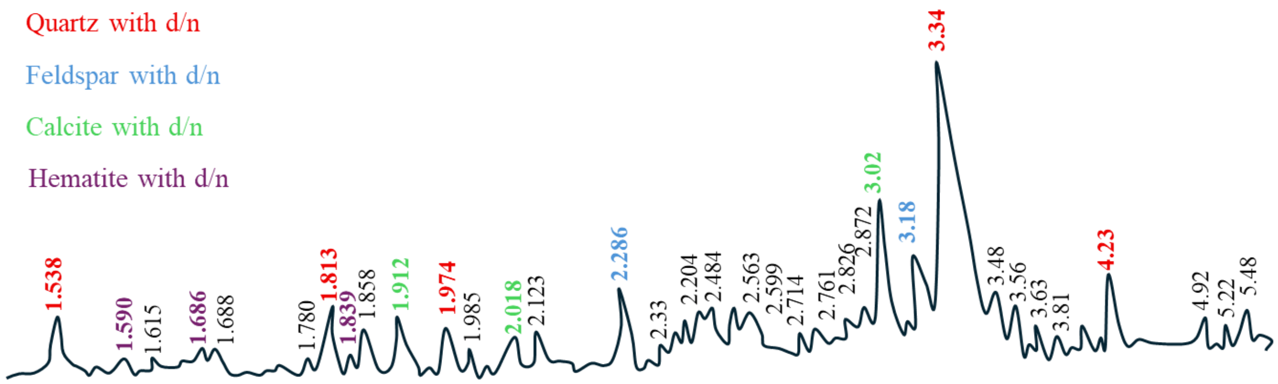


Figure 2 – X-ray diffraction pattern of low-plasticity clay from the Rubezhinsk deposit, WKR

The crystalline phases identified in the clay include quartz with d/n = 4.23, 3.34, 1.974, 1.813, and 1.538 × 10^{-10} m; feldspar with d/n = 3.18 and 2.286 × 10^{-10} m; calcite with d/n = 3.02, 2.018, and 1.912 × 10^{-10} m; and hematite with d/n = 1.839, 1.686, and 1.590 × 10^{-10} m.

Thus, it was established that the studied low-plasticity clay is predominantly composed of mixed kaolinite–hydromica mineral systems. In terms of technological characteristics, the loam is sensitive to drying and exhibits low molding properties, which may not always be favorable for the production of porous ceramics.

As a mineral additive for the production of gas-ceramics, a siliceous rock – opoka – from the Taskala deposit in the WKR was used.

The opoka from the Taskala deposit is a lightweight, hard, microporous sedimentary rock. It is characterized by high natural porosity (55-60%). According to geological data, opoka is found in Paleogene and Cretaceous formations, typically formed in marine basins through the compaction and cementation of diatomites and tripoli.

Its density ranges from 1.3 to 1.5 g/cm³. These are white or grayish, sometimes greenish lightweight rocks, occasionally containing remnants of diatom algae, radiolarians, and sponge spicules.

X-ray diffraction analysis (Figure 3) showed that the primary mineral phase is amorphous silica (SiO_2).

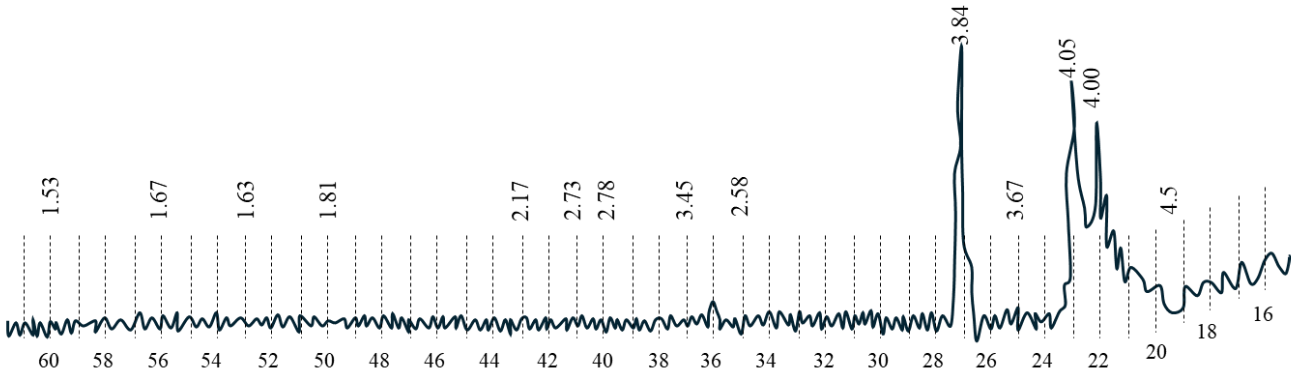


Figure 3 – X-ray diffraction pattern of the siliceous rock (opoka) from the Taskala deposit

The selection of this raw material is justified by its natural porosity and lightness, the specificity of its chemical and mineralogical composition, the presence of a large deposit in the West Kazakhstan Region, and the multifactorial influence of this additive during the stages of high-porosity ceramic production. This assertion is supported by numerous studies conducted by researchers involved in the development of porous ceramic production technologies [17], [18], [19].

Hydrogen peroxide (GOST 177-88) with the chemical composition H_2O_2 (perhydrol), medical grade, was used as the foaming agent.

To ensure the required structural integrity of the porous clay masses and the strength of the final products, it was proposed to introduce a fine mineral additive into the clay slip formulation. For this purpose, finely ground powder of the siliceous rock opoka was used.

One of the key technological operations in the production of porous ceramic materials is the preparation of the slip. In laboratory conditions, this was carried out as follows: the clay material was pre-dried and sieved through a mesh with 1 mm openings.

The additive used had a specific surface area of up to 3000 cm^2/g and a microporosity of 0.8-1 cm^3/g.

The mineral additive (opoka), along with 60% of the total water volume (at a temperature of 30–60°C), was mixed using a mechanical mixer for 5 minutes. Hydrogen peroxide was then added in an amount of 2-3% relative to the water content, and the mixture was stirred for an additional 1-1.5 minutes. The resulting slip was poured into molds (Figure 4), taking into account the calculated expansion coefficient. After molding, the samples were immediately dried in a laboratory drying oven at a temperature of 70-80°C until a residual moisture content of 5-7% was reached.

Figure 4 – Slip for gas-ceramic production poured into molds

The expansion coefficient was determined as the ratio of the volume of the expanded slip to the volume of the initial molding slip.

3. Results and Discussion

At the initial stage, a fine-dispersed mineral additive in the form of siliceous rock (opoka) was introduced into the slip based on low-plasticity clay in amounts ranging from 10% to 30% to study the relationship between additive content and the degree of sedimentation. For comparative analysis, a control sample consisting of slip based solely on low-plasticity clay (without additives) was used.

Figure 5 illustrates the effect of the corrective mineral additive – siliceous opoka – on the sedimentation behavior of the expanded mass based on low-plasticity clay.

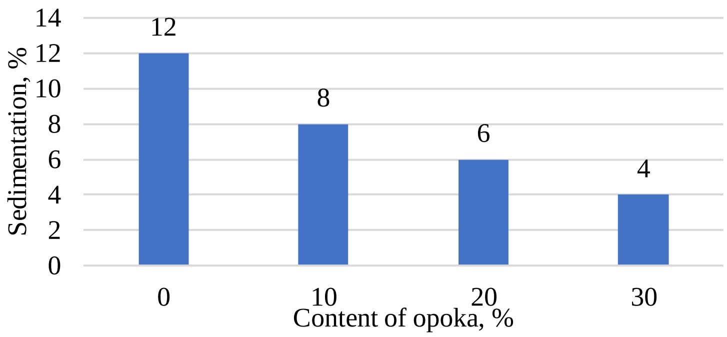


Figure 5 – Effect of the mineral additive (opoka) on the sedimentation of porous slip based on low-plasticity clay from the Rubezhinsk deposit

The research results demonstrate that the introduction of fine-dispersed, highly porous mineral additives in the form of siliceous rock (opoka) into the slip reduces the sedimentation of molded samples and the shrinkage of the products during drying. For example, the sedimentation of samples based on slip from low-plasticity clay without additives was 12%. With the addition of the mineral additive (opoka), a gradual reduction in sedimentation was observed. The maximum reduction occurred at an opoka content of 30%, resulting in a sedimentation of only 4%.

Thus, the findings at this stage of the study suggest that the incorporation of fine, highly porous siliceous mineral additives (opoka) into the slip accelerates the development of structural strength in the molding mass by 10-15% and reduces the sedimentation of molded samples during drying by 33-66%.

Figure 6 shows fragments of laboratory measurements of sample sedimentation after drying.

Figure 6 – Fragments of sedimentation measurements of porous samples after drying

After drying, the porous samples were fired in a laboratory muffle electric furnace at a temperature of 1000 °C, with a heating rate of 100 °C per hour and a holding time of 1 hour at the peak temperature. Upon completion of the firing process, the samples were cooled inside the switched-off furnace to room temperature.

Figure 7 presents the general appearance of the samples before and after firing.

a) After drying, before firing b) After firing at t = 950 °C

Figure 7 – Gas-ceramic samples

The fired samples were tested to determine their physico-mechanical properties. The results of the physico-mechanical tests are presented in Table 4.

Table 4 – Physico-mechanical properties of gas-ceramic samples

Composition No.	Average density, kg/m³	Compressive strength, MPa	Total porosity, %	Thermal conductivity, W/m·°C
1	785	2.5	68.4	0.24
2	715	2.7	71.2	0.22
3	680	3.1	73.4	0.20
4	565	3.8	75.2	0.18

The technology for producing gas-ceramic porous materials is continuously being improved in many countries through the incorporation of various mineral additives [20], [21], [22], [23].

However, in Kazakhstan, research on the development of highly porous gas-ceramic materials using siliceous rock (opoka) from the WKR remains limited and insufficiently explored.

As the results of this study show, the addition of a highly porous, fine-dispersed mineral additive in the form of siliceous opoka to low-plasticity clay slip has a positive effect on the physico-mechanical properties of gas-ceramics.

In particular, the inclusion of 10% to 30% of this mineral additive reduces the average density of the material from 785 kg/m³ to 565 kg/m³, representing a 28.8% decrease compared to samples made from clay slip without the additive.

The mineral additive also contributes to an increase in the total porosity of the samples, from 68.4% to 75.2%, which constitutes an increase of 9.0% to 10% relative to the control samples.

In addition, improvements were observed in compressive strength and reductions in thermal conductivity. Specifically, the compressive strength increased from 2.5 MPa to 3.8 MPa, while the thermal conductivity decreased from 0.24 W/m·°C to 0.18 W/m·°C compared to the clay slip samples without the additive.

This effect is likely attributed to the high natural porosity of the siliceous opoka and its ability to undergo sintering under firing temperatures [24], [25], [26].

The findings of this study are in good agreement with the work of researchers focused on the development of highly porous ceramics from various raw material sources [27], [28], [29].

Across the literature review, two distinct pathways to sustainable construction materials emerge: (i) lightweight porous ceramics for thermal efficiency and (ii) chemically solidified or modified binders/soils for mechanical capacity. In this study, low-plasticity Rubezhinsk clay, enhanced with 10–30% Taskala opoka (amorphous-silica-rich, highly porous), produced fired gas-ceramics with very low density (565–785 kg/m³), high total porosity (68–75%), and low thermal conductivity (0.18–0.24 W/m·°C) at modest compressive strengths (2.5–3.8 MPa). Opoka cut drying sedimentation by 33–66% and accelerated structure build-up, with 20–30% opoka giving the best strength–insulation balance – an envelope-grade material ideally suited to cold climates.

By contrast, the binder/soil route prioritizes strength and durability. The LGF (lime–GGBS–fly ash) system for freeze–thaw–affected silty clays identified an optimal 4:14:6 mix at 18% content; microanalysis showed synergistic C–S–H/C–A–H formation, and a PSO–BP model ($R^2 \approx 0.982$) accurately predicted UCS under cyclic freezing, highlighting LGF and clay contents as dominant factors. For gypsum soils, lime+GGBS with fly ash improved UCS most at 28 days via ettringite and silica gel growth, while overgrowth at 56 days reduced strength—underscoring time-dependent sulfate chemistry. Biomass-ash stabilization of purple soil, after 800 °C treatment, strengthened soil across curing regimes via salt/calcite cementation (dry) and multi-component bonding with mineral damage/re-contact (humid), demonstrating a cement-free valorization path. Kaolin excavation waste solidified with MgO or CaO (early oven curing) achieved far higher 28-day strengths (≈20.3 vs 12.2 MPa) than the porous ceramics here; MgO's advantage came from fibrous nesquehonite and fewer micro-cracks, marking it a greener alternative to CaO/PC for waste-to-binder conversion.

Within cementitious composites, sepiolite at 2.5% (pre-absorbent) acted as an internal-curing, fiber-reinforcing, and nucleation agent, raising compressive and flexural strengths by ~18% and ~51% and refining pores. Bentonite as a partial PC replacement delivered an optimum at ~5% (≈95% strength gain vs control and ~31% lower thermal conductivity when combined with cold-bonded GGBFS aggregates), but >15% bentonite degraded properties—illustrating dosage sensitivity. Sargassum ash in ceramics favored 10% at 900–1000 °C, improving mechanics while LCA flagged sintering energy as the dominant impact.

Taken together, this study's opoka-modified gas-ceramics provide superior insulation at low density for building envelopes, while the other works deliver higher structural strengths, freeze–thaw resilience, internal curing, and waste valorization through chemically driven densification. The portfolios are complementary: use this study's materials where thermal efficiency and light weight are paramount, and deploy the binder/soil and composite strategies where load-bearing capacity, durability under environmental cycles, or maximum waste utilization are the primary objectives.

4. Conclusion

Based on the results of the conducted research, the following conclusions can be drawn regarding the potential of low-plasticity clay and siliceous rock (opoka) as raw materials for the production of porous gas-ceramic materials:

1) The low-plasticity clay from the Rubezhinsk deposit contains 68% SiO_2, 11.8% Al_2O_3, 3.6% Fe_2O_3, and 5.6% CaO, with a plasticity index of 6.5%, classifying it as low-plasticity. It is sensitive to drying (cracking begins after 50–60 s). XRD analysis revealed quartz, feldspar, calcite, and hematite as the main crystalline phases. The siliceous rock (opoka) from the Taskala deposit is characterized by a density of 1.3-1.5 g/cm³ and high natural porosity of 55–60%, with amorphous silica as the dominant phase.

2) The addition of finely dispersed opoka (10–30%) to the clay slip reduced sedimentation of molded samples during drying from 12% (without additive) to 4% (with 30% opoka), i.e., a reduction by 33–66%. It also accelerated the development of structural strength in the molding mass by 10-15%.

3) The fired gas-ceramic samples exhibited average densities of 565–785 kg/m³, compressive strength of 2.5-3.8 MPa, total porosity of 68.4-75.2%, and thermal conductivity of 0.18-0.24 W/m·°C.

4) Samples with 20-30% opoka demonstrated the most favorable balance of low density (565–680 kg/m³), increased strength (up to 3.8 MPa), and minimum thermal conductivity (0.18 W/m·°C), confirming the effectiveness of siliceous additives in enhancing the structural and insulating performance of porous ceramics.

5) The combination of high porosity, low thermal conductivity, and adequate mechanical strength makes the developed gas-ceramic materials suitable for use as structural-thermal insulation components in building envelope systems, particularly in cold climates such as the northern regions of Kazakhstan.

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Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence (AI): The authors declare that AI was not used.

Received: 17.07.2025
Revised: 09.09.2025
Accepted: 17.09.2025
Published: 21.09.2025