Technobius, 2025, 5(4), 0091, DOI: https://doi.org/10.54355/tbus/5.4.2025.0091

Technobius

https://technobius.kz/

e-ISSN 2789-7338

Article

Low thermal conductivity silica ceramics based on diatomite modified with loam

Azamat Taskaliev*, Bekbulat Shakeshev, Kanat Narikov, Beksultan Idrisov, Kamar Dzhumabaeva

West Kazakhstan Innovation and Technological University, Uralsk, Republic of Kazakhstan
*Correspondence: taskalievazamat@mail.ru

Abstract. This study investigates diatomite-based silica ceramics designed for low thermal conductivity, using diatomite from the Utesai deposit (Aktobe region, Kazakhstan) and loam from the Romanovskoye deposit (West Kazakhstan region, Kazakhstan) as a modifying additive. The raw diatomite is characterized by high porosity and low thermal conductivity, while the ground fraction shows favorable technological behavior for ceramic processing, including low drying sensitivity. Calcination at 950 °C increases density and thermal conductivity, indicating partial densification. Silica-ceramic specimens were produced by plastic and semi-dry molding and fired at 950 °C, both from pure diatomite and from a diatomite-loam composition. The results show that 10% loam addition improves the fired structure: density and strength increase, whereas water absorption and total shrinkage decrease, with only minor changes in thermal conductivity. The combined trends demonstrate the feasibility of producing lightweight silica ceramics with improved integrity while maintaining heat-insulating performance.
Keywords: diatomite, silica ceramics, loam additive, thermal conductivity, water absorption.

1. Introduction

Diatomite is a biochemical rock belonging to the group of siliceous stones [1], consisting of minerals of the silicon oxide group - opal - amorphous silica [2]. Diatomite deposits are stratiform in shape, and in some cases, they have the form of flattened lenses with a relatively consistent thickness [3]. Diatomite can be characterized as a loose or cemented siliceous rock, white or light gray in color, consisting of more than 50% of diatom shells, containing 70-98% silica, with high porosity up to 75% and low bulk density from 420 to 1250 kg/m^3 [4]. It is used as a hydraulic additive for the production of Portland cement, lightweight concrete, ceramic and thermal insulation products, filler for the production of plastics, rubber, and paints [5].

The construction industry is currently focused on expanding its raw material base through the use of low-plasticity clays, loams, opal-cristobalite, and other silica-containing rocks [6]. In this regard, the industrial use of diatomite is based on a number of its physical and chemical properties that allow it to be used as a multi-purpose raw material, such as sound and heat conductivity, resistance to chemical reactions, and fire resistance [7].

[8] studied the effect of firing temperatures of 900, 1000, and 1100 °C on the transformation of the silicon dioxide phase during the manufacture of ceramic products from diatomite. Diffractometry results confirm the suitability of diatomite for the production of ceramic, construction, and thermal insulation materials. According to [9], the effect of the elastic modulus of diatomite on porosity varies in the range from 240 to 50 MPa when the porosity of the medium changes from 20 to 60%, and the tensile strength of the material changes by ≈ 10 MPa with a change in porosity.

To obtain porous silica ceramics with firing temperatures of 1000, 1150, and 1300 °C, [10] used diatomite with an additive of boric acid in an amount of up to 2 %, which had a positive effect on pore distribution. Studies of modified samples [11] of silica ceramics using clay, diatomite, and boric acid additives showed that the resulting materials had a low Young's modulus, which means they can be deformed under forces that negatively affect their strength.

According to [12], silica ceramics obtained at a firing temperature of 1000 °C had a compressive strength of 20.96 MPa and a thermal conductivity coefficient of 0.29 W/(m·K). In other studies, the strength was 35 MPa with a thermal conductivity coefficient of 0.16 W/(m·K) [13] and 50 MPa [14].

While previous studies have made progress in the physical and mechanical properties of silica ceramics, they mainly used firing temperatures of 1000 °C and above, which leaves a potential for reducing energy losses, an important aspect currently. Therefore, this research aims to develop a technology for the production of silica ceramics designed to minimize heat exchange between the environment and the interior of buildings and structures, with low heating and ventilation costs. The research results are important for the application of diatomite, a unique natural material, in providing high-quality building materials for civil and industrial buildings and structures.

2. Methods

This study incorporated a diatomite from the Utesai deposit (Aktobe region, Kazakhstan) as a main siliceous raw material, and a loam from the Romanovskoye deposit (West Kazakhstan region, Kazakhstan) as a modifying additive.

To determine the physical properties of the diatomite rock, cubic specimens (100 mm edge length) were prepared by sawing from diatomite pieces. The average density [15] was determined by weighing using ACS electronic scales (HUADE Ltd., Shanghai, China). Thermal conductivity [16] was measured using an ITP-MG-4 ZOND device (“Special Design Bureau Stroypribor” LLC, Chelyabinsk, Russia). For ceramic-technology studies, diatomite pieces were ground to obtain a fraction with particle sizes <2 mm (Figure 1) using an MShL-1 laboratory ball mill (NPK Mekhanobr-Technika, St. Petersburg, Russian Federation). To evaluate the effect of high-temperature treatment on diatomite properties, the <2 mm diatomite fraction was fired at 950 °C in an EKPS 50/1300 electric furnace (Smolensk SKTB SPU, Smolensk, Russia), producing calcined diatomite (i.e., thermolite).

Figure 1 – Finely ground (left) and fired (right) diatomite

Silica-ceramic laboratory specimens were produced as Ø50 mm × 50 mm cylinders. For forming and testing operations, an LO-257 mold (RNPO RusPribor LLC, St. Petersburg, Russia) and a PGM-50MG4 press (SKB Stroipribor LLC, Chelyabinsk, Russia) were used (Figure 2). Two forming routes were used [17]: plastic molding and semi-dry molding. Specimens were produced from (i) 100% diatomite and (ii) a mixture of 90% diatomite + 10% loam (by mass). After shaping, specimens were dried in an SNOL 67/350 unit (Smolensk SKTB SPU, Smolensk, Russia) and then fired at 950 °C in an EKPS 50/1300 electric furnace.

Figure 2 – Compression test of samples

For diatomite, the following properties were determined [18]: average density and thermal conductivity (rock cubes), bulk density, thermal conductivity, plasticity coefficient, adhesion (stickiness), and drying sensitivity coefficient (ground fraction).

For thermolite (calcined diatomite), bulk density and thermal conductivity were determined after firing at 950 °C.

For fired silica-ceramic specimens, the following properties were determined: average density, compressive strength, thermal conductivity, water absorption, and total shrinkage for both forming routes (plastic and semi-dry) and for both compositions (0% and 10% loam).

3. Results and Discussion

The diatomite rock shows (Table 1) a consistently low average density (~950 kg/m³) coupled with low thermal conductivity (~0.132 W/(m·K)) and very high porosity (~64%). Such a combination is characteristic of highly porous siliceous materials: the pore network reduces heat transfer, while also limiting mechanical load-bearing capacity. The small spread between replicate samples indicates stable properties for the studied diatomite source.

Table 1 – Physical properties of diatomite (100 mm rock cubes)

Sample	Average density, kg/m^3	Thermal conductivity, W/(m·K)	Porosity, %
1	948	0.131	64.1
2	952	0.133	63.9
3	950	0.132	64.0
Average value	950	0.132	64.0

For ceramic processing, the diatomite fraction (<2 mm) remains lightweight (bulk density ~410 kg/m³) and shows very low thermal conductivity (~0.098 W/(m·K)), consistent with its highly porous structure (Table 2). The plasticity coefficient (~5.88), low adhesion (~8.8 g/cm²), and very low drying sensitivity (~0.173) indicate that this diatomite fraction is weakly adhesive and relatively insensitive to drying, which is technologically favorable (less risk of drying cracks and less sticking to tooling). In contrast, loam is much denser (1425 kg/m³) and much more thermally conductive (0.84 W/(m·K)). It also has a substantially higher plasticity coefficient (15.6) and adhesion (22.3 g/cm²), meaning it can function as a binder/plasticizing component. However, its high drying sensitivity coefficient (1.8) implies that loam-rich bodies would be more prone to drying defects if drying is not controlled. Therefore, using loam as a limited additive is logically consistent: it can improve shaping/green strength and firing behavior without fully inheriting the drying risks of loam.

Table 2 – Comparison of average technological properties: diatomite vs loam

Material	Bulk density, kg/m^3	Thermal conductivity, W/(m·K)	Plasticity coefficient	Adhesion, g/sm^2	Drying sensitivity coefficient
Diatomite	410	0.098	5.88	8.8	0.173
Loam	1425	0.84	15.6	22.3	1.8

After firing the diatomite fraction at 950 °C, the bulk density increases markedly to ~725 kg/m³, while thermal conductivity rises to ~0.11 W/(m·K), as shown in Table 3. This increase is expected: firing reduces the open porosity and increases solid-phase connectivity (densification and/or partial sintering), which improves heat conduction through the solid skeleton. In practical terms, calcination shifts the material from an extremely porous powder to a denser, thermally more conductive product.

Table 3 – Bulk density and thermal conductivity of thermolite (calcined diatomite at 950 °C)

Sample	Bulk density, kg/m^3	Thermal conductivity, W/(m·K)
1	725	0.11
2	726	0.12
3	724	0.10
Average value	725	0.11

Table 4 shows the properties of silica ceramics produced by plastic molding.

Table 4 – Physical and mechanical properties of plastic-molded silica ceramics

Composition	Average density, kg/m^3	Strength, MPa	Thermal conductivity, W/(m·K)	Water absorption, %	Complete shrinkage, %
Diatomite	918.5	100	0.11	55	5.6
Diatomite (90%) and loam (10%)	1015.5	110	0.112	45	4.2

As is seen from Table 5, for plastic-molded silica ceramics fired at 950 °C, ceramics based on 100% diatomite show an average density of 918.5 kg/m³ and thermal conductivity of ~0.11 W/(m·K). Water absorption is high (55%), indicating a significant fraction of open pores, which is consistent with the raw diatomite's porous nature. Introducing 10% loam increases density (to 1015.5 kg/m^3) and strength (from 100 to 110), while reducing water absorption (from 55% to 45%) and total shrinkage (from 5.6% to 4.2%). The direction of these changes is internally consistent: loam likely promotes stronger particle bonding and a more continuous fired structure (better packing and/or formation of binding phases during firing), which reduces the volume of interconnected open pores. Thermal conductivity increases only slightly (from 0.11 to 0.112), which is expected when density increases and porosity decreases.

Table 5 shows the properties of silica ceramics produced by semi-dry molding.

Table 5 – Physical and mechanical properties of semi-dry molded silica ceramics

Composition	Average density, kg/m^3	Strength, MPa	Thermal conductivity, W/(m·K)	Water absorption, %	Complete shrinkage, %
Diatomite	1014.2	75	0.11	48	6.7
Diatomite (90%) and loam (10%)	1086.5	83	0.112	42	4.8

As is seen from Table 5, semi-dry molded ceramics show higher densities than plastic-molded ones for both compositions (1014.2 vs. 918.5 kg/m^3 for pure diatomite; 1086.5 vs. 1015.5 kg/m³ for the loam-containing mix). Correspondingly, water absorption is lower (48% vs. 55% for pure diatomite; 42% vs. 45% for the loam mix), which aligns with the denser structure. However, strength is lower for semi-dry molded samples than for plastic-molded samples (75 vs. 100 for pure diatomite; 83 vs. 110 for the loam mix), and total shrinkage is higher (6.7 vs. 5.6; 4.8 vs. 4.2). Interpreting these results together suggests that higher "bulk density" from semi-dry molding does not automatically translate into higher mechanical performance; likely because strength is influenced not only by density but also by how uniformly particles bond and whether defects (e.g., lamination planes, incomplete interparticle contact, microcracking from constrained shrinkage) form during forming/drying/firing. Plastic molding can provide more uniform particle rearrangement and bonding, which may explain the higher measured strengths despite slightly lower densities. As in plastic molding, adding 10% loam improves the semi-dry results: density increases (from 1014.2 to 1086.5), strength rises (from 75 to 83), and water absorption drops (from 48% to 42), while shrinkage decreases (from 6.7% to 4.8). This supports the same functional role of loam as a reinforcing/structure-forming additive in fired bodies.

Across all datasets, the key controlling factor is porosity: the raw diatomite's very high porosity explains its low thermal conductivity, but it also leads to high water absorption in fired ceramics unless the structure is partially densified. Calcination increases density and thermal conductivity, indicating pore reduction and stronger solid connectivity.

For fired silica ceramics at 950 °C, the 10% loam addition consistently improves performance in both forming routes: it increases density and strength while reducing water absorption and shrinkage. This combination is technologically important because it indicates that small loam contents can enhance the integrity of the fired structure without causing a large penalty in thermal conductivity (only a slight increase is observed).

When comparing forming routes, semi-dry molding produces denser bodies with lower water absorption, but the measured strength is lower, and shrinkage is higher than for plastic molding. For applications where mechanical reliability is critical, the plastic-molding route appears more favorable based on the strength results reported, while semi-dry molding may be more suitable when lower water absorption (via higher density) is prioritized, especially when combined with a loam additive.

4. Conclusion

The investigated Utesai diatomite is a highly porous siliceous raw material (porosity ≈64%), which explains its low thermal conductivity (≈0.132 W/(m·K)) at a relatively low average density (≈950 kg/m³). In ground form (<2 mm), diatomite remains lightweight (bulk density ≈410 kg/m³) and thermally efficient (≈0.098 W/(m·K)) while showing low drying sensitivity, indicating good technological suitability for ceramic processing. Firing at 950 °C converts the diatomite into a denser, thermally more conductive product (thermolite: bulk density ≈725 kg/m³; thermal conductivity ≈0.11 W/(m·K)), consistent with partial densification and reduced open porosity.

Silica ceramics fired at 950 °C demonstrate that both the forming route and composition govern the balance between strength and moisture-related properties. Adding 10% loam to diatomite consistently improves performance in both plastic and semi-dry molding: density increases (by ~7-11%), strength rises (by ~10-11% as reported), water absorption decreases (by ~12-18%), and total shrinkage reduces (by ~25-28%), while thermal conductivity changes only slightly (from ≈0.11 to ≈0.112 W/(m·K)). Comparing forming routes, semi-dry molding yields higher density and lower water absorption, whereas plastic molding provides higher strength for the studied compositions. Overall, a diatomite-based body with a limited loam addition (10%) is the most balanced option among those tested, enabling low thermal conductivity alongside improved structural integrity and reduced water uptake.

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Information about authors:

Azamat Taskaliev – Master of Technical Sciences, Lecturer, Department of Architecture and Civil Engineering, West Kazakhstan Innovation and Technological University, Uralsk, Republic of Kazakhstan, taskalievazamat@mail.ru
Bekbulat Shakeshev – Candidate of Technical Sciences, Rector, West Kazakhstan Innovation and Technological University, Uralsk, Republic of Kazakhstan, bekshakeshev@mail.ru
Kanat Narikov – Candidate of Technical Sciences, Lecturer, Department of Architecture and Civil Engineering, Uralsk, Republic of Kazakhstan, knarik1969@mail.ru
Beksultan Idrisov – Master of Technical Sciences, Lecturer, Department of Architecture and Civil Engineering, West Kazakhstan Innovation and Technological University, Uralsk, Republic of Kazakhstan, beksultan.idirisov@mail.ru
Kamar Dzhumabaeva – Master of Technical Sciences, Lecturer, Department of Architecture and Civil Engineering, West Kazakhstan Innovation and Technological University, Uralsk, Republic of Kazakhstan, zhumabaeva12.02.88@gmail.com

Author Contributions:

Azamat Taskaliev – concept, project making, analysis.
Bekbulat Shakeshev – resources, methodology.
Kanat Narikov – project making, editing.
Beksultan Idrisov – data collection, visualization.
Kamar Dzhumabaeva – testing, interpretation.

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

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

Received: 13.10.2025
Revised: 22.12.2025
Accepted: 23.12.2025
Published: 25.12.2025