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RESEARCH ARTICLE

PROPERTIES OF ECO-FRIENDLY CERAMIC MATERIALS BASED ON FLY ASH AND RICE HUSK

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Abstract. *This study examines the feasibility of producing sustainable ceramic materials from locally available loess-like loam, fly ash from a thermal power plant, liquid glass, and ground rice husk. The work is motivated by two parallel challenges: the need to reduce the consumption of high-quality clay in traditional ceramic production and the need to valorize industrial and agricultural wastes that are otherwise landfilled, stockpiled, or openly burned. In the proposed system, loess-like loam serves as the basic aluminosilicate matrix, fly ash acts as a fine mineral component rich in silica and alumina, liquid glass functions as a fluxing and structure-promoting additive, and rice husk plays a dual role as an internal fuel and a silica-bearing pore-forming modifier during firing. The investigated raw mixes contained 40.0–53.5 wt.% loess-like loam, 42.0–52.0 wt.% fly ash, 4.0–6.0 wt.% liquid glass, and 0.5–2.0 wt.% ground rice husk. Samples were prepared by semi-dry pressing and fired at 900–1000 °C. According to the reported experimental results, the developed compositions achieved compressive strengths in the range of 28–35 MPa, water absorption of 15–18%, and frost resistance up to 62 freeze–thaw cycles. Compared with the reference composition, the modified ceramic system showed a broader high-strength range, lower water absorption, and better frost durability. SEM observations revealed a denser microstructure in the modified compositions, while XRD analysis confirmed the formation of quartz, cristobalite, mullite, anorthite, and hematite phases. The results demonstrate that the combined use of fly ash and rice husk contributes to matrix densification, improved durability characteristics, and effective utilization of industrial and agricultural waste in ceramic production.*

Keywords: *rice husk, fly ash, ceramic materials, raw mix, loess-like loam, water absorption, frost resistance, compressive strength.*

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ҒЫЛЫМИ МАҚАЛА

ҰШПА КҮЛ МЕН КҮРІШ ҚАУЫЗЫ НЕГІЗІНДЕГІ ЭКОЛОГИЯЛЫҚ ТАЗА КЕРАМИКАЛЫҚ МАТЕРИАЛДАРДЫҢ ҚАСИЕТТЕРІ

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Аңдатпа. *Бұл зерттеу жергілікті қолжетімді лесс тәрізді саздақтан, жылу электр станциясының ұшпа күлінен, сұйық шыныдан және ұнтақталған күріш қауызы негізінде тұрақты керамикалық материалдар өндірудің мүмкіндігін қарастырады. Зерттеу екі негізгі мәселені шешуге бағытталған: дәстүрлі керамика өндірісінде жоғары сапалы сазды тұтынуды азайту және әдетте көміліп, үйінділерде сақталатын немесе ашық түрде жағылатын өнеркәсіптік және ауылшаруашылық қалдықтарын тиімді пайдалану. Ұсынылған жүйеде лесс тәрізді саздақ негізгі алюмосиликатты матрица қызметін атқарады, ал ұшпа күл кремний мен алюминийге бай ұсақ минералдық компонент ретінде қолданылады. Сұйық шыны балқыту қасиетін арттыратын және құрылым түзуші қоспа ретінде қызмет етеді, ал күріш қауызы күйдіру кезінде ішкі отын әрі кремнийлі кеуек түзуші модификатор ретінде екі түрлі рөл атқарады. Зерттелген шикізат құрамдары 40.0–53.5 мас.% лесс тәрізді саздақтан, 42.0–52.0 мас.% ұшпа күлден, 4.0–6.0 мас.% сұйық шыныдан және 0.5–2.0 мас.% ұнтақталған күріш қауызынан тұрды. Үлгілер жартылай құрғақ престеу әдісімен дайындалып, 900–1000 °C температурада күйдірілді. Алынған тәжірибелік нәтижелерге сәйкес, әзірленген құрамдардың қысу кезіндегі беріктігі 28–35 МПа аралығында, су сіңіргіштігі 15–18%, ал аязға төзімділігі 62 мұздату-еріту циклына дейін жетті. Сонымен қатар, СЭМ талдауы модификацияланған құрамдардың анағұрлым тығыз микрокұрылымын көрсетті, ал рентгендік фазалық талдау (XRD) кварц, кристобалит, муллит, анортит және гематит фазаларының түзілуін растады. Алынған нәтижелер ұшпа күл мен күріш қауызын бірлесіп пайдаланудың матрицаның тығыздалуына, беріктік пен төзімділік қасиеттерінің жақсаруына және өнеркәсіптік әрі ауыл шаруашылығы қалдықтарын керамикалық материалдар өндірісінде тиімді кәдеге жаратуға ықпал ететінін көрсетті.*

Түйін сөздер: *күріш қауызы, күл-ұшпа, керамикалық материалдар, шикізат қоспасының құрамы, лесс тәрізді саздақ, су сіңіргіштік, аязға төзімділік, сығылу беріктігі.*

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НАУЧНАЯ СТАТЬЯ

СВОЙСТВА ЭКОЛОГИЧЕСКИ ЧИСТЫХ КЕРАМИЧЕСКИХ МАТЕРИАЛОВ НА ОСНОВЕ ЗОЛЫ-УНОСА И РИСОВОЙ ЛУЗГИ

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Аннотация. *Данное исследование посвящено оценке возможности получения устойчивых керамических материалов на основе местного лессовидного суглинка, золы-уноса тепловой электростанции, жидкого стекла и измельчённой рисовой лузги. Работа обусловлена двумя актуальными задачами: снижением потребления высококачественной глины в традиционном керамическом производстве и утилизацией промышленных и сельскохозяйственных отходов, которые в противном случае складируются, захораниваются или сжигаются на открытом воздухе. В предлагаемой системе лессовидный суглинок выполняет роль основной алюмосиликатной матрицы, зола-уноса выступает в качестве тонкодисперсного минерального компонента, богатого кремнезёмом и глинозёмом. Жидкое стекло действует как плавневая и структурообразующая добавка, а рисовая лузга выполняет двойную функцию: внутреннего топлива и кремнезёмсодержащего порообразующего модификатора в процессе обжига. Исследованные составы сырьевых смесей включали 40.0–53.5 мас.% лессовидного суглинка, 42.0–52.0 мас.% золы-уноса, 4.0–6.0 мас.% жидкого стекла и 0.5–2.0 мас.% измельчённой рисовой лузги. Образцы формовали методом полусухого прессования с последующим обжигом при температуре 900–1000 °C. Согласно полученным экспериментальным данным, разработанные составы обеспечивают прочность при сжатии в диапазоне 28–35 МПа, водопоглощение 15–18% и морозостойкость до 62 циклов замораживания-оттаивания. Кроме того, результаты СЭМ-анализа показали более плотную микроструктуру модифицированных составов, тогда как рентгенофазовый анализ (XRD) подтвердил образование кварца, кристобалита, муллита, анортита и гематита. Полученные результаты свидетельствуют о том, что совместное использование золы-уноса и рисовой лузги способствует уплотнению матрицы, улучшению показателей долговечности и эффективной утилизации промышленных и сельскохозяйственных отходов в производстве керамических материалов.*

Ключевые слова: *рисовая лузга, зола-уноса, керамические материалы, состав сырьевой смеси, лессовидный суглинок, водопоглощение, морозостойкость, прочность при сжатии.*

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1. INTRODUCTION

The development of sustainable ceramic materials has attracted increasing attention due to the growing demand for resource-efficient construction products and the need to utilize industrial and agricultural waste. Conventional ceramic products are commonly manufactured from high-quality clay raw materials and require energy-intensive firing processes. Therefore, considerable research efforts have focused on the partial replacement of traditional clay with waste-derived materials such as fly ash, rice husk, and rice husk ash, which can reduce raw-material consumption and contribute to more sustainable ceramic production [1-4].

A recent study by [4] demonstrated that rice husk ash can be successfully incorporated into clay ceramics as a secondary silica source. The authors reported that moderate additions of rice husk ash improved processing behavior and enabled the production of ceramic blocks with satisfactory physical and mechanical properties.

Fly ash is one of the most widely studied industrial by-products in ceramic and cementitious technologies. Owing to its high silica and alumina content, fine particle size, and partially amorphous structure, fly ash can act as both a mineral filler and a chemically active constituent in thermally treated systems. Previous studies have shown that fly ash can improve packing density, modify vitrification behavior, reduce the consumption of natural clay, and contribute to the production of ceramic materials with satisfactory mechanical and durability properties [1; 5-7].

Rice husk and rice husk ash have also received considerable attention as renewable waste-derived materials. Rice husk is rich in organic matter and contains a substantial amount of silica. During thermal treatment, the organic fraction decomposes and can contribute internal heat, while the silica-bearing residue may participate in the formation of glassy or reactive phases depending on combustion conditions. In many studies, rice husk-derived materials have been used either as pore-forming agents, fuel additives, or silica-rich modifiers. The challenge is that their effect is strongly dosage-dependent: a small addition may improve thermal efficiency or pore refinement, whereas excessive contents can raise porosity and reduce strength [1; 2-4].

Recent literature continues to confirm the relevance of this research direction. For example, a 2024 study on eco-friendly clay ceramics with rice husk ash reported that the appropriate dosage of rice husk ash must be carefully selected to maintain acceptable processing conditions and final performance. In parallel, a 2025 review on fired clay bricks with organic additives emphasized that the best-performing systems are obtained when the addition level, firing regime, and target property profile are balanced rather than optimized for only one parameter. These studies reinforce the idea that waste-derived ceramic bodies should be designed as integrated systems in which chemistry, processing, and pore formation are considered simultaneously [3; 4; 9].

Another important research direction is the utilization of low-grade local soils such as loess-like loam in ceramic production. Such materials are abundant in many regions of Central Asia, including Kazakhstan, yet they are often underutilized because of their variable mineralogy and lower plasticity compared with conventional ceramic clays. Nevertheless, when combined with industrial by-products and properly selected additives, loess-like soils can serve as alternative aluminosilicate raw materials for the production of sustainable ceramic products while reducing the consumption of high-quality clay resources [10-14].

The present study investigates ceramic materials produced from loess-like loam of the Kyzylorda region, fly ash from the Kyzylorda thermal power plant, liquid glass, and ground rice husk. The proposed composition combines industrial and agricultural waste materials within a single ceramic system. Loess-like loam serves as the primary aluminosilicate matrix, fly ash provides silica- and alumina-rich mineral components, liquid glass acts as a fluxing additive promoting liquid-phase formation during firing, and rice husk functions as a pore-forming and silica-bearing modifier. The combined use of these components aims to improve the physical and mechanical properties of ceramic materials while reducing the consumption of conventional clay raw materials.

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Compared with the current literature, the value of this work lies less in the isolated use of fly ash or rice husk and more in the region-specific integration of these materials into a semi-dry pressed ceramic composition based on local loess-like loam. In addition, the study targets a technologically practical firing range of 900–1000 °C, which is lower than the temperatures often associated with conventional high-strength ceramic processing. From a manufacturing perspective, this is important because energy demand and production cost are strongly related to maximum firing temperature and soaking time [8; 9].

Investigated ceramic bricks incorporating rice husk and thermal power plant ash [15]. The authors demonstrated that the combined use of agricultural and industrial waste additives can improve the physical and mechanical properties of fired ceramic materials while reducing the consumption of conventional clay raw materials.

More recently, [16] investigated ceramic materials produced using clay, thermal power plant ash, and rice husk ash from the Kyzylorda region. The authors reported that the optimal composition containing 70% clay, 20% thermal power plant ash, and 10% rice husk ash achieved the highest compressive strength of 15.45 MPa, reduced water absorption, and improved densification. Microstructural and phase analyses confirmed that the improved performance was associated with partial vitrification and the formation of crystalline phases such as mullite, cristobalite, and anorthite.

Building upon these previous studies, the present work investigates a ceramic system based on local loess-like loam, fly ash, liquid glass, and ground rice husk. Unlike the previous formulations, the proposed composition incorporates liquid glass as a fluxing additive and utilizes loess-like loam as the primary aluminosilicate raw material, enabling the production of ceramic materials at firing temperatures of 900–1000 °C.

Recent studies have demonstrated the growing interest in the utilization of industrial waste and advanced ceramic materials in sustainable construction. The use of ash and slag waste from thermal power plants for building ceramics was investigated by [16]. The potential application of CHP ash in the production of fired ash gravel was reported by [17]. In addition, the development and optimization of porous ceramic materials based on SiO_2–SiC systems were studied by [18-20]. These studies confirm the growing interest in resource-efficient and environmentally sustainable construction materials.

The scientific novelty of the present study lies in the combined utilization of fly ash, liquid glass, and ground rice husk in a ceramic system based on local loess-like loam from the Kyzylorda region. While previous studies have mainly focused on the separate use of fly ash or rice husk ash in conventional clay-based ceramics, the present work investigates their synergistic interaction within a semi-dry pressed ceramic composition produced at a relatively low firing temperature of 900–1000 °C. In addition, the study demonstrates the feasibility of replacing a significant portion of traditional clay raw materials with locally available industrial and agricultural waste resources while maintaining satisfactory mechanical and durability properties.

Therefore, the objective of this work was to investigate the feasibility of producing sustainable ceramic materials from loess-like loam, fly ash, liquid glass, and ground rice husk, and to evaluate how this raw-mix concept affects compressive strength, water absorption, frost resistance, and firing behavior. The study also aims to provide a clearer technological interpretation of the roles played by each component and to identify the practical advantages and current limitations of the proposed material system.

2. MATERIALS AND METHODS

2.1. Raw materials

Four principal raw materials were used to prepare the ceramic bodies: loess-like loam, fly ash, liquid glass, and ground rice husk. Loess-like loam obtained from the Kyzylorda region was used as the principal aluminosilicate component replacing conventional high-grade clay. The material was selected because of its regional availability and potential for low-cost large-scale use in wall ceramics.

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Fly ash was collected from the Kyzylorda thermal power plant. According to the chemical data reported in the study, the ash contained approximately 45.45–46.37% SiO_2, 16.62–17.70% Al_2O_3, 1.66–2.20% CaO, 0.86–1.12% MgO, 2.98–3.41% Fe_2O_3, and 0.80–1.04% alkali oxides. Such composition allows the ash to be considered a silica- and alumina-bearing semi-acid ceramic raw material with potential to participate in sintering and phase development.

Liquid glass (sodium silicate solution) with a density of 1.3–1.5 g/cm³ was used as a fluxing additive. Its expected function in the ceramic body was to facilitate early liquid-phase formation, improve particle bonding, and support densification during thermal treatment.

Rice husk was used as a structure-modifying additive. Before use, it was ground in a laboratory drum mill to a specific surface area of approximately 1000–1200 cm²/g in order to promote more uniform distribution in the mixture and more stable combustion during firing. In the present work, rice husk was not treated merely as a combustible organic addition; rather, it was considered a multifunctional component capable of affecting internal heat release, pore formation, and silica availability.

Table 1 – Reported oxide composition of the fly ash used in the study [Author's materials].

№	Oxide	Content (%)
1	SiO_2	45.45–46.37
2	Al_2O_3	16.62–17.70
3	CaO	1.66–2.20
4	MgO	0.86–1.12
5	Fe_2O_3	2.98–3.41
6	Alkali oxides	0.80–1.04

2.2. Raw-mix design

The investigated raw mixes were designed to contain 40.0–53.5 wt.% loess-like loam, 42.0–52.0 wt.% fly ash, 4.0–6.0 wt.% liquid glass, and 0.5–2.0 wt.% ground rice husk. The formulation logic was to keep loam as the base matrix, use fly ash as the main corrective mineral component, apply liquid glass as a sintering aid, and vary the rice husk content in order to evaluate its effect on strength, water absorption, and frost resistance.

In the present manuscript, the rice husk fraction is treated as the principal variable of interest because the reported trends clearly show that its addition affected both compressive strength and water absorption. The available experimental results suggest that the investigated range of 0.5–2.0 wt.% is sufficiently low to avoid excessive weakening while still allowing the additive to influence firing behavior and pore development.

Table 2 – Reported composition range of the investigated raw mixtures [Author's materials].

№	**Component**	**Content (wt.%)**
1	Loess-like loam	40.0–53.5
2	Fly ash	42.0–52.0
3	Liquid glass	4.0–6.0
4	Ground rice husk	0.5–2.0

2.3. Sample preparation and firing regime

The ceramic specimens were prepared by the semi-dry pressing route, which is widely used in industrial brick production. The loess-like loam and fly ash were first dried at 105 °C to constant mass and sieved to remove coarse particles. The mineral components were then dosed and homogenized in a disintegrator-type mixer. Liquid glass was introduced under continuous agitation, followed by the gradual addition of the ground rice husk. The moisture content of the final mixture was adjusted to approximately 9%, after which the specimens were formed by semi-dry pressing.

The reported specimen dimensions were 120 × 60 × 30 mm. After shaping, the samples were dried and then fired in a laboratory furnace. The firing program included a heating rate of 5–10

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°C/min, a peak temperature in the range of 900–1000 °C, a holding time of 1–2 h at the maximum temperature, and natural cooling inside the furnace. The temperature interval was selected to evaluate whether the combination of liquid glass and rice husk could support the formation of sufficiently strong ceramic bonds at lower firing temperatures than those often used in conventional systems.

2.4. Test methods and data treatment

The key response parameters considered in the study were compressive strength, flexural strength, water absorption, and frost resistance. Compressive strength was determined according to GOST 8462, while water absorption and frost resistance were evaluated according to the relevant GOST procedures for ceramic materials. Frost resistance was assessed by cyclic freezing and thawing.

For each composition, three specimens were prepared and tested under identical conditions (n = 3). The reported values represent the arithmetic mean of the measured results. Due to the unavailability of the complete primary dataset, standard deviations, confidence intervals, and other statistical indicators could not be reliably reconstructed and therefore are not reported in the present study.

The present manuscript relies on the experimentally reported property ranges rather than on a full specimen-by-specimen dataset. Therefore, the charts included in the revised version are intended to visualize the reported ranges and trends and to support interpretation of the results rather than to present a new statistical analysis. Additional experimental details such as replicate number, standard deviation, and full mix-by-mix property matrices would further strengthen the manuscript and are recommended for future expanded reporting.

2.5. Microstructural and phase composition analysis

The microstructure of the fired ceramic samples was examined using a JSM-6390LV scanning electron microscope (JEOL, Japan). Fractured surfaces of representative specimens were analyzed to evaluate the morphology, pore distribution, and structural features of the ceramic matrix. Energy-dispersive X-ray spectroscopy (EDS) was additionally employed to determine the qualitative elemental composition of the investigated samples.

The phase composition of the ceramic materials was determined by X-ray diffraction (XRD) using an X'Pert PRO diffractometer (PANalytical, Netherlands) with CuKα radiation (λ = 1.5406 Å). Diffraction patterns were recorded in the 2θ range of 10–80°. The obtained diffraction peaks were compared with reference diffraction data to identify the crystalline phases formed during firing.

The combined SEM, EDS, and XRD analyses were used to establish the relationship between microstructure, phase composition, and the physical and mechanical properties of the developed ceramic materials.

3. RESULTS AND DISCUSSION

The developed raw-mix composition and technological approach are protected by patent of the Republic of Kazakhstan [21] which confirms the novelty and practical applicability of the proposed solution. The patented compositions are based on the use of loess-like loam, fly ash, liquid glass, and ground rice husk within optimized content ranges, which ensure improved mechanical and durability properties of ceramic products. The technological parameters reported in the patents indicate that the use of such compositions allows reducing the firing temperature and obtaining materials with controlled density and water absorption [16]. These data are consistent with the experimental results obtained in the present study, confirming the feasibility and practical applicability of the proposed raw-mix design.

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3.1. Overall performance of the developed ceramic system

The reported experimental results indicate that the developed ceramic compositions based on loess-like loam, fly ash, liquid glass, and rice husk achieved a compressive-strength range of 28–35 MPa. Although the ranges partly overlap, the developed system shows a clear shift toward higher strength values and, importantly, maintains improved durability-related indicators at the same time. This suggests that the proposed formulation strategy does not merely enhance one isolated property, but affects the material system more broadly.

A similar trend is observed for water absorption and frost resistance. The developed compositions showed water absorption in the range of 15–18%, whereas the reference composition was reported at 17–20%. Even a moderate reduction of several percentage points is technologically meaningful in fired ceramic materials because water absorption is closely linked to open porosity, capillary transport, and long-term durability. The reported frost resistance of up to 62 freeze–thaw cycles further indicates that the pore structure formed during drying and firing is not excessively coarse or interconnected.

The reported experimental results indicate that the developed ceramic compositions achieved compressive strengths ranging from 28 to 35 MPa. A similar trend is observed for water absorption and frost resistance. The developed compositions showed water absorption in the range of 15–18%, whereas the reference composition was reported at 17–20%. Even a moderate reduction of several percentage points is technologically meaningful in fired ceramic materials because water absorption is closely linked to open porosity, capillary transport, and long-term durability. The reported frost resistance of up to 62 freeze–thaw cycles further indicates that the pore structure formed during drying and firing is not excessively coarse or interconnected.

To provide a more detailed presentation of the experimental results, the compositions investigated in this study and their corresponding performance indicators are summarized in Table 3. The table includes the composition of each mixture together with compressive strength, water absorption, and frost resistance values.

Table 3 – Experimental results of the investigated ceramic compositions [Author's materials].

№	Mix	Loess-like loam (wt.%)	Fly ash (wt.%)	Liquid glass (wt.%)	Rice husk (wt.%)	Compressive strength (MPa)	Water absorption (%)	Frost resistance (cycles)
1	M1	53.5	42.0	4.0	0.5	28	18	45
2	M2	49.5	45.0	4.5	1.0	30	17	50
3	M3	45.5	49.0	5.0	1.5	32	16	56
4	M4	40.0	52.0	6.0	2.0	35	15	62

Note: All reported values correspond to the average of three specimens (n = 3).

Table 3 presents the experimental results obtained for the investigated ceramic compositions. An increase in rice husk content from 0.5 to 2.0 wt.% was accompanied by an increase in compressive strength from 28 to 35 MPa and a decrease in water absorption from 18% to 15%. Frost resistance also improved from 45 to 62 cycles, indicating a more favorable pore structure and enhanced durability of the ceramic body.

In addition to the experimental results, the developed material system is supported by a patented technological approach. Patent No. 36668 describes a method for manufacturing artificial porous materials based on loess-like loam and fly ash with the addition of a finely dispersed organomineral mixture containing rice husk . According to the patent, the use of such an additive system contributes to a reduction in firing temperature and allows obtaining lightweight materials with

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controlled density and water absorption . These characteristics are consistent with the results obtained in the present study, confirming the technological feasibility of the proposed approach.

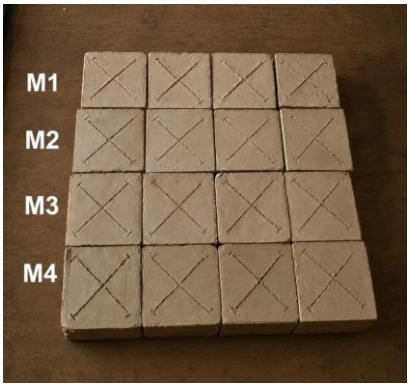


Figure 1 – Appearance of fired ceramic specimens produced from the investigated raw mixtures. [Author's materials]

3.2. Physical and mechanical properties of the investigated ceramic compositions

This finding is noteworthy because organic additives often weaken fired clay bodies when used in excessive quantities. The fact that a small rice-husk addition increased compressive strength while simultaneously reducing water absorption suggests that the additive did not simply generate large open pores. Instead, the observed behavior is more consistent with a controlled thermochemical contribution. During heating, the rice husk likely decomposed gradually, released internal heat inside the ceramic body, and left behind a fine silica-bearing residue. Under suitable firing conditions, this can help improve the uniformity of sintering and support the formation of a finer pore network rather than a severely damaged one.

Table 3 and Figure 2 present the physical and mechanical properties of the investigated ceramic compositions. As the content of fly ash, liquid glass, and rice husk increased and the proportion of loess-like loam decreased, compressive strength increased from 28 MPa for composition M1 to 35 MPa for composition M4. At the same time, water absorption decreased from 18% to 15%, while frost resistance increased from 45 to 62 cycles.

The observed improvement in properties indicates that the modified compositions developed a denser and more stable ceramic structure during firing. The combined action of fly ash, liquid glass, and rice husk contributed to enhanced densification and reduced open porosity, which resulted in higher strength, lower water absorption, and improved frost resistance. Among the investigated formulations, composition M4 demonstrated the most favorable balance of physical and mechanical properties.

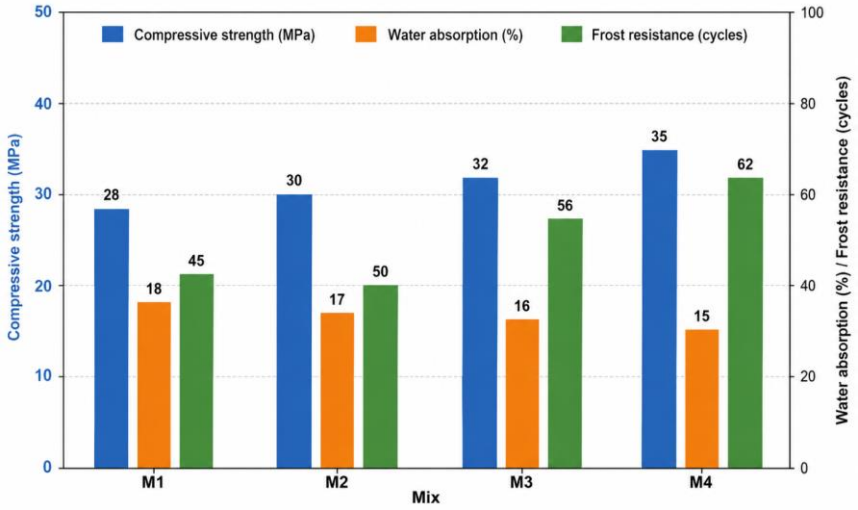


Figure 2 – Physical and mechanical properties of the investigated ceramic compositions**.** [Author's materials]

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3.3. Microstructural observations

Microstructural observations were performed using scanning electron microscopy (SEM). Figure 3 presents SEM micrographs illustrating the microstructure of the control sample and the ceramic composition containing fly ash and rice husk additives.

The microstructure is characterized by a heterogeneous but relatively compact matrix consisting of partially sintered mineral particles and fine-grained reaction products. The observed morphology indicates the presence of both dense regions and isolated micropores formed during the thermal decomposition of rice husk. Fly ash particles appear to be well integrated into the ceramic matrix and contribute to particle packing and densification. No large interconnected pores or major structural defects were observed, which is consistent with the relatively low water absorption and satisfactory compressive strength obtained for the developed compositions. The formation of a compact microstructure supports the assumption that liquid glass promoted liquid-phase sintering and improved interparticle bonding during firing.

Compared with the control sample (Figure 3a), the modified composition (Figure 3b) exhibits a denser microstructure with a more uniform distribution of fine particles and a reduced number of large pores. This observation is consistent with the experimentally observed increase in compressive strength and decrease in water absorption. The incorporation of fly ash and rice husk appears to promote particle packing and improve the compactness of the ceramic matrix.

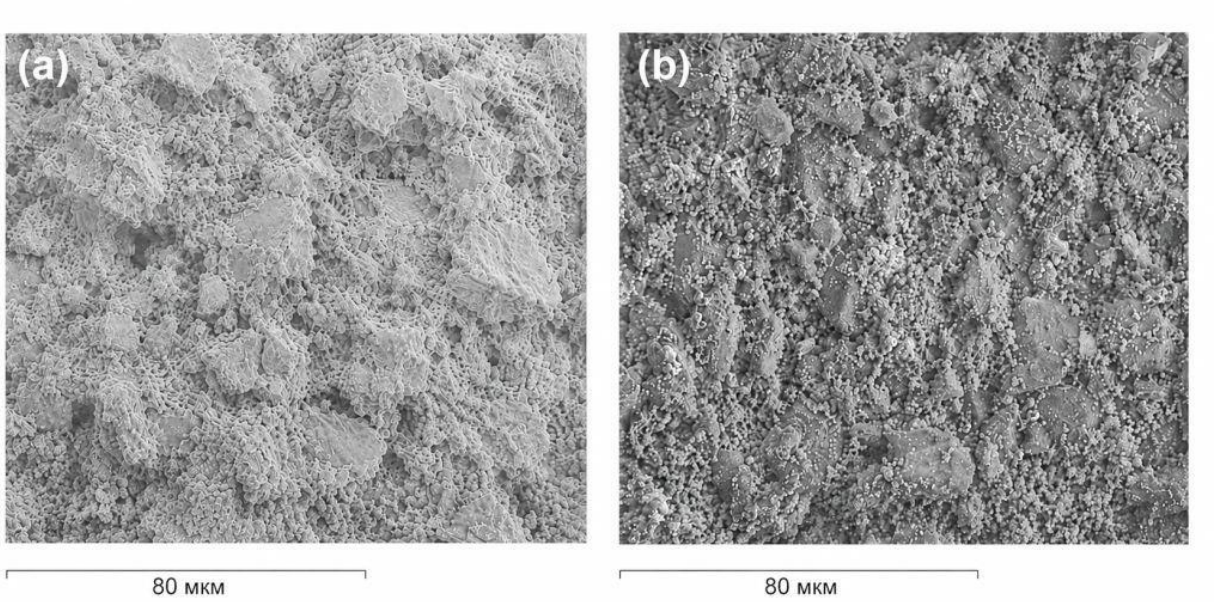


Figure 3. SEM micrographs of ceramic materials: (a) control sample without additives; (b) ceramic composition containing fly ash and rice husk additives (magnification×220, scale bar 80 μm) [Author's materials]

Table 4 – Qualitative EDS analysis of selected regions [Author's materials].

№	Spectrum	Main elements
1	S2	Si, Al, O
2	S3	Si, Al, Ca, O
3	S4	Si, O
4	S5	Si, Al, Fe, O

EDS analysis confirmed the predominance of Si, Al, and O, indicating the formation of an aluminosilicate ceramic matrix. The presence of Ca and Fe in some regions reflects the contribution of fly ash components to the development of the ceramic structure.

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The SEM and EDS results support the proposed mechanism of ceramic structure formation and confirm that the incorporation of fly ash and rice husk contributes to matrix densification, reduced porosity, and improved performance of the developed ceramic material.

3.4. Phase composition analysis

The phase composition of the fired ceramic materials was investigated by X-ray diffraction (XRD). Figure 4 presents the XRD patterns of the control sample based on pure loess-like loam (Figure 4a) and the investigated ceramic composition containing fly ash, liquid glass, and rice husk (Figure 4b).

The control sample is mainly characterized by quartz as the dominant crystalline phase, together with minor reflections of cristobalite and mullite formed during firing. In contrast, the modified composition exhibits additional reflections associated with anorthite and hematite, as well as increased intensities of mullite-related peaks. The formation of mullite, cristobalite, and anorthite indicates phase transformations and interactions between silica-, alumina-, and calcium-bearing components introduced by the additives.

The appearance of anorthite in the modified composition suggests the participation of calcium-bearing phases originating from fly ash during firing. Increased mullite reflections indicate the development of a more stable aluminosilicate framework, which is commonly associated with enhanced mechanical strength and thermal stability. These phase changes contribute to the densification of the ceramic matrix and are consistent with the improved physical and mechanical properties observed for the modified ceramic material. The XRD results therefore support the proposed mechanism of ceramic structure development and confirm the beneficial effect of fly ash and rice husk additives on phase evolution during firing.

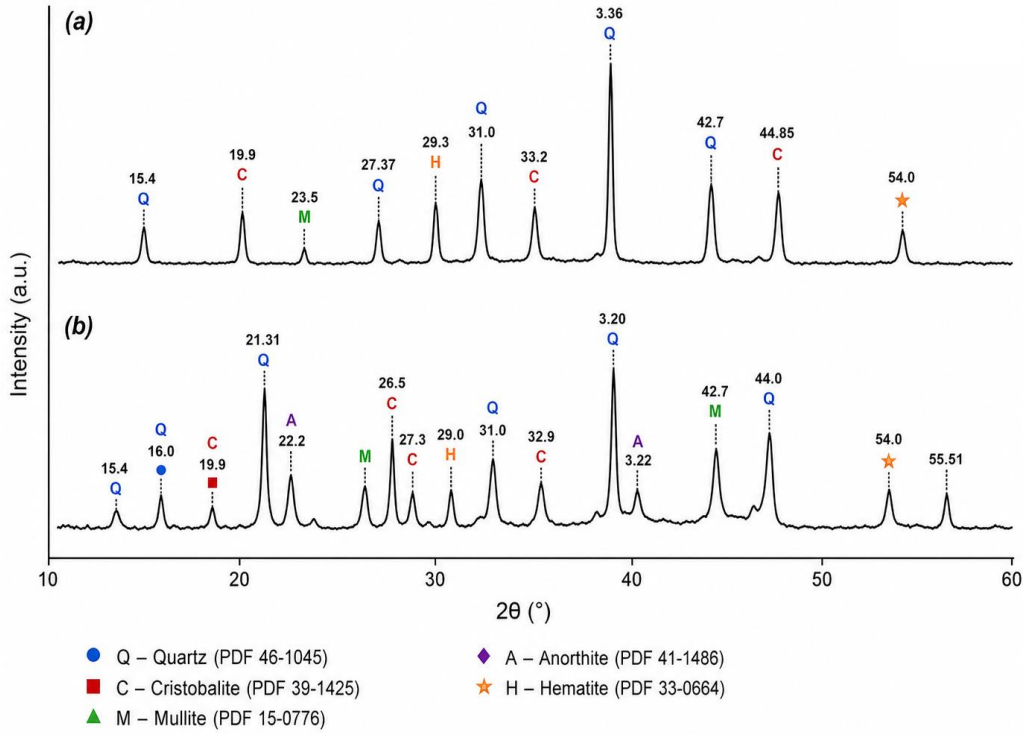


Figure 4 – XRD patterns of ceramic samples: (a) control sample based on pure loess-like loam; (b) investigated composition containing loess-like loam, fly ash, liquid glass, and rice husk [Author's materials]

The performance improvement observed in the developed ceramic body is best understood as a synergistic effect rather than the result of a single additive. Loess-like loam provides the bulk aluminosilicate framework, but on its own it may not ensure the same level of densification or property consistency as higher-grade ceramic clays. Fly ash contributes fine particles and oxide

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components that help fill voids in the green body and participate in phase development during firing. Liquid glass facilitates earlier softening and liquid-phase formation, thereby improving interparticle bonding. Rice husk, finally, acts as a multifunctional additive whose behavior extends beyond simple pore formation.

Compared with previous studies on fly ash- or rice husk-based ceramics, the present work differs in several important aspects. First, the investigated compositions are based on local loess-like loam rather than conventional ceramic clay. Second, both industrial waste (fly ash) and agricultural waste (rice husk) are simultaneously incorporated into a single ceramic system. Third, the reported performance was achieved within a relatively low firing temperature range of 900–1000 °C. These features distinguish the proposed material from previously reported ceramic compositions and demonstrate the potential of region-specific waste utilization strategies for sustainable ceramic production.

Figure 5 summarizes this synergistic concept. From a materials-engineering standpoint, the important point is that each component addresses a different technological need: loam provides volume and regional availability, fly ash improves packing and chemistry, liquid glass lowers the resistance to sintering, and rice husk affects internal heat evolution and microstructural organization. Such division of functions is one of the reasons why the developed compositions can outperform the reference composition even though they rely on non-traditional and low-cost raw materials.

The formulation is also relevant from a circular-economy perspective. Thermal power plant ash and rice husk are both waste-derived resources that usually pose disposal challenges. Their incorporation into ceramic products redirects them into a value-added application and reduces the dependence on virgin raw materials.

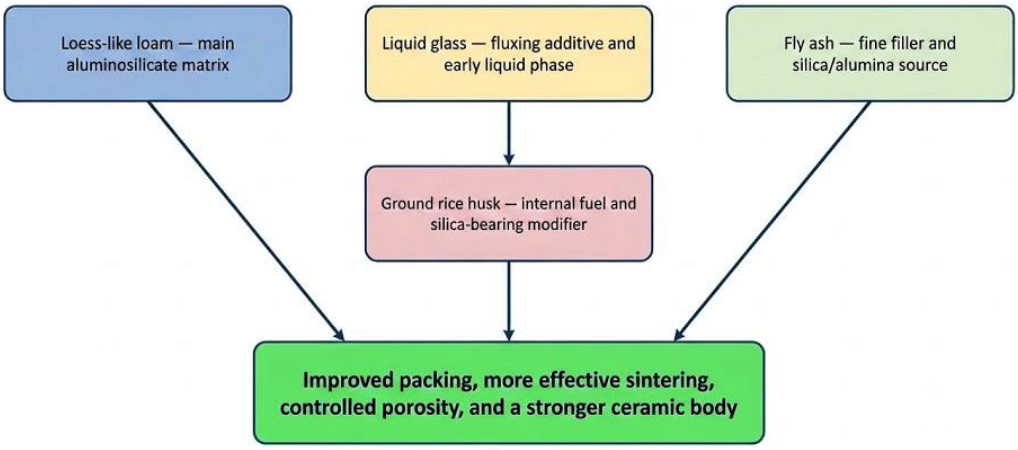


Figure 5 - Schematic illustration of the synergistic role of the main raw materials in the developed ceramic system [Author's materials]

The use of rice husk is especially important because it may influence the ceramic body in several ways during heating. First, the organic fraction burns out and contributes internal heat. This can improve temperature distribution inside the ceramic body, reduce the risk of uneven firing, and locally accelerate sintering. Second, the residue left after combustion may contain amorphous or fine silica that can interact with the mineral matrix during firing. Third, the burnout process creates micro-pores, but when the dosage is low and the pores remain sufficiently fine, these pores may remain small and discontinuous rather than becoming large connected defects. The beneficial effect of this mechanism depends strongly on the presence of other components. If rice husk were used in a purely clay-based body without adequate mineral correction, the strengthening contribution could be lost. In the present system, however, fly ash and liquid glass provide precisely the type of complementary action needed to promote improved densification.

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The proposed interpretation is supported by the experimental results obtained in the present study. SEM observations revealed a denser and more homogeneous microstructure in the modified composition compared with the control sample, together with a reduced number of large pores. EDS analysis confirmed the predominance of Si, Al, and O and indicated the presence of Ca- and Fe-bearing regions associated with fly ash incorporation. Furthermore, XRD analysis identified quartz, cristobalite, mullite, anorthite, and hematite phases in the modified ceramic body. The appearance of anorthite and the increased intensity of mullite reflections indicate phase transformations promoted by the interaction of silica-, alumina-, and calcium-bearing components during firing.

These experimental observations are consistent with the measured increase in compressive strength from 28 to 35 MPa, the reduction in water absorption from 18% to 15%, and the improvement in frost resistance from 45 to 62 cycles. Therefore, the improved performance of the developed ceramic material can be attributed not only to the individual contribution of each component but also to the combined effects of matrix densification, phase development, and controlled pore structure formation.

Figure 4 presents a conceptual firing pathway for the developed ceramic system. The figure is intentionally schematic, but it helps explain why the reported firing interval of 900–1000 °C is technologically plausible. The firing behavior of the developed ceramic system can be interpreted considering the individual functions of its components. Rice husk acts as a combustible organic additive and a source of silica-rich residue, while liquid glass promotes liquid-phase formation during firing. The obtained SEM and XRD results suggest that these components contribute to the development of a denser ceramic structure and favorable phase composition. However, the detailed thermal mechanisms occurring during firing require additional investigation using thermal analysis techniques and are beyond the scope of the present study.

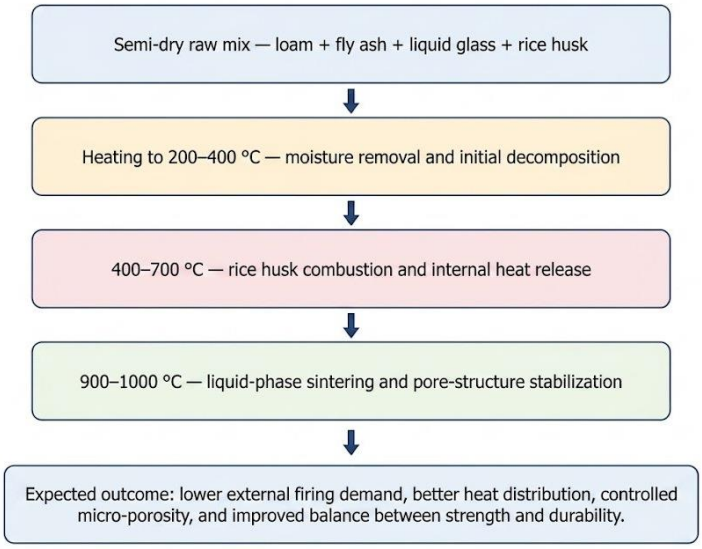


Figure 6 – Conceptual firing pathway and expected role of rice husk during thermal treatment of the ceramic body [Author's materials]

The experimental results obtained in this study demonstrate that the proposed raw-mix concept improves several important performance indicators simultaneously. The investigated compositions achieved compressive strengths of 28–35 MPa, water absorption of 15–18%, and frost resistance of up to 62 cycles. SEM observations revealed a denser microstructure, while XRD analysis confirmed the formation of quartz, cristobalite, mullite, anorthite, and hematite phases. These findings indicate that the combined use of loess-like loam, fly ash, liquid glass, and rice husk contributes to the development of a durable ceramic material with satisfactory physical and mechanical properties. Similar multi-waste ceramic strategies have been reported in the broader literature; how-

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ever, the resulting performance remains strongly dependent on local raw materials, dosage control, and firing conditions.

3.5. Limitations of the study and future research

Despite the encouraging results obtained in this study, several limitations should be acknowledged. First, the number of investigated compositions was limited to four mixtures within a relatively narrow range of rice husk content. Second, the experimental program focused mainly on compressive strength, water absorption, and frost resistance, whereas other important performance indicators such as thermal conductivity, drying shrinkage, abrasion resistance, and long-term durability were not evaluated.

Although SEM, EDS, and XRD analyses provided valuable information on the microstructure and phase composition of the developed ceramics, more detailed characterization techniques, including quantitative porosity measurements, thermal analysis (DTA/TG), and image-based pore-size distribution analysis, would provide a deeper understanding of the mechanisms governing material performance.

Future research should focus on expanding the composition matrix, optimizing the firing regime, evaluating additional durability-related properties, and performing advanced microstructural characterization. In addition, the thermal insulation performance and large-scale industrial applicability of the developed ceramic materials should be investigated to assess their potential for practical construction applications.

4. CONCLUSIONS

1. The study demonstrated the feasibility of producing ceramic materials based on loess-like loam, fly ash, liquid glass, and ground rice husk.

2. The developed ceramic compositions achieved compressive strengths of 28–35 MPa, water absorption of 15–18%, and frost resistance of 45–62 cycles, confirming their suitability for construction applications.

3. Increasing the rice husk content from 0.5 to 2.0 wt.% increased the compressive strength from 28 to 35 MPa while reducing water absorption from 18% to 15%, indicating the positive effect of the additive within the investigated range.

4. SEM observations revealed a denser and more homogeneous microstructure in the modified compositions compared with the control sample, while EDS analysis confirmed the predominance of Si, Al, and O, and XRD analysis identified the presence of quartz, cristobalite, mullite, anorthite, and hematite phases.

5. The formation of mullite and anorthite, together with improved matrix densification, was consistent with the observed enhancement in mechanical strength and frost resistance.

6. The combined use of fly ash and rice husk enables the effective recycling of industrial and agricultural waste while reducing the consumption of conventional ceramic raw materials.

7. Further research should focus on evaluating thermal conductivity, long-term durability, quantitative porosity characteristics, and the optimization of firing conditions..

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest.

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