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RESEARCH ARTICLE

EFFECT OF RICE HUSK ASH CONTENT ON THE PHYSICAL AND MECHANICAL PROPERTIES AND FREEZE–THAW RESISTANCE OF ARBOLITE

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Abstract. *This study investigates the combined use of rice husk (RH) as an organic lightweight filler and rice husk ash (RHA) as a partial Portland-cement replacement in arbolite composites. Six mixtures containing 0–20% RHA were prepared at a constant total binder content and water-to-binder ratio. Density, compressive and flexural strength, water absorption, freeze–thaw resistance, and microstructural features were evaluated. Each physical and mechanical property was determined using three specimens, and the results were processed using the arithmetic mean, standard deviation, and coefficient of variation. The optimum mixture containing 12.5% RHA reached a compressive strength of 3.8 MPa and a flexural strength of 1.8 MPa, representing increases of 26.7% and 80%, respectively, relative to the RHA-free control. Water absorption decreased from 21.5% to 17.2%. After 35 freeze–thaw cycles, the optimum mixture retained a frost-resistance coefficient of 0.65, whereas the control specimens lost structural integrity. Microscopy revealed relatively compact binder-matrix regions in the optimized composition, consistent with the measured performance trends. The scientific novelty lies in determining an RHA dosage that simultaneously balances density, strength, water absorption, and freeze–thaw resistance in rice-husk-based arbolite. The developed material is recommended for non-load-bearing wall and partition elements, provided that appropriate moisture-protective finishing is used.*

Keywords: *rice husk; rice husk ash; arbolite; lightweight concrete; water absorption; freeze–thaw resistance; agricultural waste.*

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ҒЫЛЫМИ МАҚАЛАСЫ

КҮРІШ ҚАУЫЗЫ КҮЛІ МӨЛШЕРІНІҢ АРБОЛИТТІҢ ФИЗИКАЛЫҚ-МЕХАНИКАЛЫҚ ҚАСИЕТТЕРІ МЕН АЯЗҒА ТӨЗІМДІЛІГІНЕ ӘСЕРІ

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Аңдатпа. *Бұл жұмыста күріш қауызы (КҚ) жеңіл органикалық толтырғыш ретінде, ал күріш қауызы күлі (КҚК) портландцементті ішінара алмастыратын минералдық қоспа ретінде арболит құрамында кешенді қолданылды. Жалпы байланыстырғыш мөлшері мен су-байланыстырғыш қатынасы тұрақты болған жағдайда КҚК мөлшері 0–20% аралығындағы алты құрам дайындалды. Орташа тығыздық, сығуға және иілуге беріктік, су сіңіргіштік, мұздату–ерітуге төзімділік және микроқұрылымдық ерекшеліктер зерттелді. Әрбір физикалық-механикалық көрсеткіш үш үлгі бойынша анықталып, нәтижелер арифметикалық орташа мән, стандарттық ауытқу және вариация коэффициенті арқылы өңделді. Құрамында 12,5% КҚК бар оңтайлы қоспаның сығуға беріктігі 3,8 МПа, иілуге беріктігі 1,8 МПа болды; бұл бақылау құрамымен салыстырғанда тиісінше 26,7% және 80% жоғары. Су сіңіргіштік 21,5%-дан 17,2%-ға дейін төмендеді. 35 мұздату–еріту циклінен кейін оңтайлы құрамның аязға төзімділік коэффициенті 0,65 болды, ал бақылау үлгілері құрылымдық тұтастығын жоғалтты. Микроскопиялық бақылаулар оңтайлы құрамда байланыстырғыш матрицаның салыстырмалы тығыз аймақтары бар екенін көрсетті. Зерттеудің ғылыми жаңалығы күріш қауызы негізіндегі арболит үшін тығыздық, беріктік, су сіңіргіштік және аязға төзімділік көрсеткіштерінің тиімді теңгерімін қамтамасыз ететін КҚК мөлшерін анықтаудан тұрады. Материалды ылғалдан қорғайтын әрлеу қолданылған жағдайда көтергіш емес қабырға және арақабырға элементтерінде пайдалану ұсынылады.*

Түйін сөздер: *күріш қауызы; күріш қауызы күлі; арболит; жеңіл бетон; су сіңіргіштік; аязға төзімділік; ауыл шаруашылығы қалдықтары.*

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НАУЧНАЯ СТАТЬЯ

ВЛИЯНИЕ СОДЕРЖАНИЯ ЗОЛЫ РИСОВОЙ ШЕЛУХИ НА ФИЗИКО-МЕХАНИЧЕСКИЕ СВОЙСТВА И МОРОЗОСТОЙКОСТЬ АРБОЛИТА

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Аннотация. *В работе исследовано совместное применение рисовой шелухи (РШ) в качестве легкого органического заполнителя и золы рисовой шелухи (ЗРШ) в качестве частичной замены портландцемента в арболитовых композитах. При постоянном расходе вяжущего и водовяжущем отношении изготовлены шесть составов с содержанием ЗРШ 0–20%. Определены средняя плотность, прочность при сжатии и изгибе, водопоглощение, сопротивление циклическому замораживанию–оттаиванию и особенности микроструктуры. Каждый физико-механический показатель определяли на трех образцах; результаты обрабатывали с использованием среднего арифметического, стандартного отклонения и коэффициента вариации. Оптимальный состав с 12,5% ЗРШ достиг прочности при сжатии 3,8 МПа и при изгибе 1,8 МПа, что соответственно на 26,7% и 80% выше контрольного состава без ЗРШ. Водопоглощение снизилось с 21,5% до 17,2%. После 35 циклов замораживания–оттаивания коэффициент морозостойкости оптимального состава составил 0,65, тогда как контрольные образцы утратили структурную целостность. Микроскопические наблюдения выявили в оптимизированном составе сравнительно плотные участки матрицы вяжущего, согласующиеся с изменением эксплуатационных показателей. Научная новизна заключается в установлении дозировки ЗРШ, обеспечивающей одновременно благоприятное сочетание плотности, прочности, водопоглощения и морозостойкости арболита на основе рисовой шелухи. Разработанный материал рекомендуется для ненесущих стеновых и перегородочных элементов при условии применения влагозащитной отделки.*

Ключевые слова: *рисовая шелуха; зола рисовой шелухи; арболит; легкий бетон; водопоглощение; морозостойкость; сельскохозяйственные отходы.*

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1 INTRODUCTION

The construction industry is under increasing pressure to reduce its environmental impact, particularly in terms of greenhouse gas emissions and resource consumption. Ordinary Portland cement (OPC), the main binder used in construction, contributes approximately 7–8% of global CO_2 emissions, making it a key target for sustainability-driven innovations [1-3]. Consequently, the incorporation of industrial and agricultural waste into cement-based materials has emerged as an effective strategy for reducing both environmental impact and material costs.

Among agricultural residues, rice husk (RH) is one of the most abundant lignocellulosic wastes, with global production exceeding 100 million tons annually. The disposal of RH poses environmental challenges due to its low biodegradability and high silica content [4,5]. Controlled combustion of rice husk produces rice husk ash (RHA), a highly reactive pozzolanic material rich in amorphous silica [6-8]. Numerous studies have demonstrated that partial replacement of cement with RHA enhances compressive strength and durability due to pozzolanic reactions and filler effects [9-12]. The pozzolanic reactivity of RHA has been further confirmed by its ability to refine pore structure and improve long-term performance [21,22].

In parallel, there has been a growing interest in the development of lightweight bio-based cementitious composites, particularly wood concrete (arbolite), which traditionally incorporates organic fillers. These materials are characterized by low density, good thermal insulation, and reduced environmental footprint [13-15]. Natural fibers and agricultural residues have been widely studied as reinforcement components in cement-based composites [16-18]. Additional studies have highlighted the importance of fiber treatment in improving adhesion and durability [19,20].

Recent research has explored rice husk as an alternative filler due to its low density, fibrous structure, and wide availability. Rice husk-based composites demonstrate promising thermal and acoustic properties and can be effectively used in lightweight construction materials [23-25]. These materials are particularly suitable for non-structural and insulating applications.

However, the direct incorporation of rice husk into cementitious matrices remains challenging due to the presence of soluble sugars, hemicellulose, and waxes, which inhibit cement hydration and reduce strength [18,19]. In addition, the high porosity and water absorption capacity of RH negatively affect workability and durability of composites [20].

Previous studies by the authors have demonstrated the potential of arbolite composites based on rice husk and multicomponent binders, including strength improvement, optimization of mixture composition, and mathematical modeling of agricultural-waste-based composite materials [27,28,30,31].

Despite the growing body of literature, two related gaps remain. First, most studies examine either RHA as a supplementary cementitious material in conventional concrete or untreated rice husk as a bio-aggregate; substantially fewer studies consider their combined use in a low-density arbolite matrix. Second, the available literature rarely evaluates mechanical properties, water absorption, and freeze–thaw resistance within one experimental program, although these characteristics must be considered together when selecting a composition for wall products.

The scientific novelty of this study is the establishment of a performance-based optimum RHA replacement level for rice-husk arbolite. The replacement level was selected not from compressive strength alone, but from the combined response of density, compressive and flexural strength, water absorption, residual strength after freeze–thaw cycling, and qualitative microstructural observations.

Accordingly, the objective was to determine how replacing 0–20% of Portland cement with RHA affects the principal physical, mechanical, and durability-related properties of rice-husk-based arbolite and to identify a composition suitable for practical lightweight wall applications.

The working hypothesis was that a moderate RHA dosage would improve the continuity of the binder phase through microfilling and pozzolanic effects, whereas excessive replacement would increase water demand and reduce the amount of Portland cement available for early matrix formation.

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The practical significance is associated with the conversion of locally available agricultural residues from the Kyzylorda region into lightweight construction products. The proposed composite is intended primarily for non-load-bearing wall blocks and partition elements. For exterior or intermittently wet service, protective rendering or another moisture-resistant finish is required because the material retains the relatively high water absorption typical of bio-aggregate concretes.

2 MATERIALS AND METHODS

Ordinary Portland cement (OPC) of strength class CEM I 42.5N was used as the primary binder (GOST 31108-2020).

Rice husk (RH), obtained from local agricultural sources, was used as a lightweight organic filler. Prior to use, the RH was cleaned to remove impurities and dried at 105 °C for 24 h to eliminate moisture.

Rice husk ash (RHA) was produced by controlled combustion of rice husk at temperatures of 600–700 °C, followed by grinding to achieve high fineness. The resulting RHA was used as a mineral additive and as a partial replacement for Portland cement.

Aluminum sulfate and calcium chloride were used as mineralizing additives to reduce the adverse influence of water-soluble organic substances from rice husk on cement hydration.

Potable water complying with GOST 23732-2011 was used for mixing.

The experimental program was designed to investigate the effect of partial Portland cement replacement with rice husk ash on the properties of arbolite composites. The RHA replacement levels were 0%, 5%, 10%, 12.5%, 15%, and 20% by mass of the total binder. The total binder content was maintained constant at 320 kg/m³. The rice husk content was fixed at 240 kg/m³, and the water-to-binder ratio was maintained at 0.50 for all mixtures. Aluminum sulfate and calcium chloride were used as mineralizing additives at constant dosages of 5 and 3 kg/m³, respectively.

Table 1 - Mix proportions of composites [Author's material]

Mix ID	RHA, % of total binder mass	RH, kg/m³	Cement, kg/m³	RHA, kg/m³	Aluminum sulfate, kg/m³	Calcium chloride, kg/m³	W/B
M0	0	240	320	0	5	3	0.50
M1	5	240	304	16	5	3	0.50
M2	10	240	288	32	5	3	0.50
M3	12.5	240	280	40	5	3	0.50
M4	15	240	272	48	5	3	0.50
M5	20	240	256	64	5	3	0.50

Note: RHA replaced an equivalent mass of Portland cement, while the total binder content was maintained constant at 320 kg/m³. The water-to-binder ratio was calculated based on the total mass of cement and RHA.

Cement and RHA were initially dry-mixed for 2–3 min to ensure uniform distribution of the mineral component. The dried rice husk was then introduced and mixed thoroughly. Aluminum sulfate and calcium chloride were dissolved in the mixing water and gradually added to the dry mixture. Mixing was continued for an additional 3–5 min until a homogeneous arbolite mixture was obtained.

The mixtures were cast into molds (100 × 100 × 100 mm cubes for compressive strength and 100 × 100 × 400 mm prisms for flexural strength). Specimen preparation and curing were performed following standard procedures for cement-based composite materials. Due to the lightweight nature of the mixtures, compaction was carried out manually.

After casting, the specimens were covered with plastic sheets to prevent moisture loss and demolded after 24 h. The specimens were subsequently cured under standard temperature and humidity conditions at 20 ± 2 °C until testing at 28 days.

Bulk density was determined by measuring the mass and volume of hardened specimens.

Compressive and flexural strength tests were performed using a universal testing machine at a loading rate of 0.5 MPa/s.

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Water absorption was determined by immersing oven-dried specimens in water for 24 h and measuring the corresponding mass increase.

Freeze–thaw resistance was evaluated using 100 × 100 × 100 mm cube specimens. For each mixture, three specimens were tested at each selected exposure level (15, 25, and 35 cycles), and three reference specimens were used to determine the initial compressive strength. Before freeze–thaw cycling, the specimens were saturated with water at 20 ± 2 °C by immersion to one-third of their height for 24 h, to two-thirds of their height for a further 24 h, and then completely immersed for 48 h. Each cycle consisted of freezing the specimens in air at −18 ± 2 °C for at least 4 h, followed by thawing in water at 20 ± 2 °C for 2 ± 0.5 h. After the specified number of cycles, the residual compressive strength was determined. The frost resistance coefficient (Kfr) was calculated as the ratio of the residual compressive strength after freeze–thaw cycling to the initial compressive strength. The freeze–thaw procedure was conducted in accordance with GOST 10060-2012.

Microstructural analysis was performed using transmission electron microscopy (TEM) to evaluate the effect of RHA on the microstructure and densification of the cementitious matrix.

2.1 Statistical analysis

For each mixture, three independent specimens ($n = 3$) were tested for density, compressive strength, flexural strength, and water absorption. The arithmetic mean was calculated as $\bar{x} = \Sigma x_i/n$, the sample standard deviation as $SD = [\Sigma(x_i - \bar{x})^2/(n - 1)]^{1/2}$, and the coefficient of variation as $CV = 100 \cdot SD/\bar{x}$. The observed SD ranges and maximum coefficients of variation are summarized in Table 2. The CV did not exceed 5% for density and 8% for mechanical properties, indicating acceptable repeatability for exploratory material testing. Because only three specimens were available per composition, the analysis emphasizes effect size and reproducibility rather than unsupported inferential p-values. In particular, the differences between the control and the optimum M3 mixture were several times greater than the maximum observed SD for compressive strength, flexural strength, and water absorption, supporting the practical reliability of the identified trend.

Table 2 – Statistical characteristics of density, strength, and water absorption results (n = 3) [Author's material]

Property	Number of specimens (n)	Observed SD range and repeatability criterion
Density	3	8–15 kg/m³; CV ≤ 5%
Compressive strength	3	0.10–0.18 MPa; CV ≤ 8%
Flexural strength	3	0.05–0.12 MPa; CV ≤ 8%
Water absorption	3	0.4–0.8 percentage points

The reported values in the figures and discussion are arithmetic means. The ranges in Table 2 describe the scatter observed among the six mixture series; measurement uncertainty was controlled through identical specimen dimensions, curing conditions, equipment, loading rate, and test procedure.

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3 RESULTS AND DISCUSSION

3.1 Density of composites

The bulk density decreased systematically as the RHA replacement level increased (Figure 1), from 800 kg/m³ for M0 to 590 kg/m³ for M5. Because the rice-husk content, total binder content, and W/B ratio were unchanged, this reduction is attributed mainly to the lower bulk density of RHA relative to Portland cement and to the greater entrainment of fine ash particles within the porous bio-aggregate skeleton. The decrease was therefore composition-dependent rather than a consequence of changing the amount of organic filler.

All values are means of three specimens. The observed density SD of 8–15 kg/m³ was small compared with the 210 kg/m³ difference between M0 and M5, confirming that the downward trend was substantially larger than the experimental scatter.

The density interval of 590–800 kg/m³ places all mixtures within the lightweight-material range. This classification is consistent with recent rice-husk-based building products developed for non-load-bearing and thermal-insulation applications [34]. However, the material reported in [34] was a non-cementitious insulation panel; therefore, it is cited only to demonstrate the building-material potential of rice husk and not for direct mechanical comparison. In the present study, density reduction must be considered together with strength and moisture resistance rather than treated as an independent optimization target.

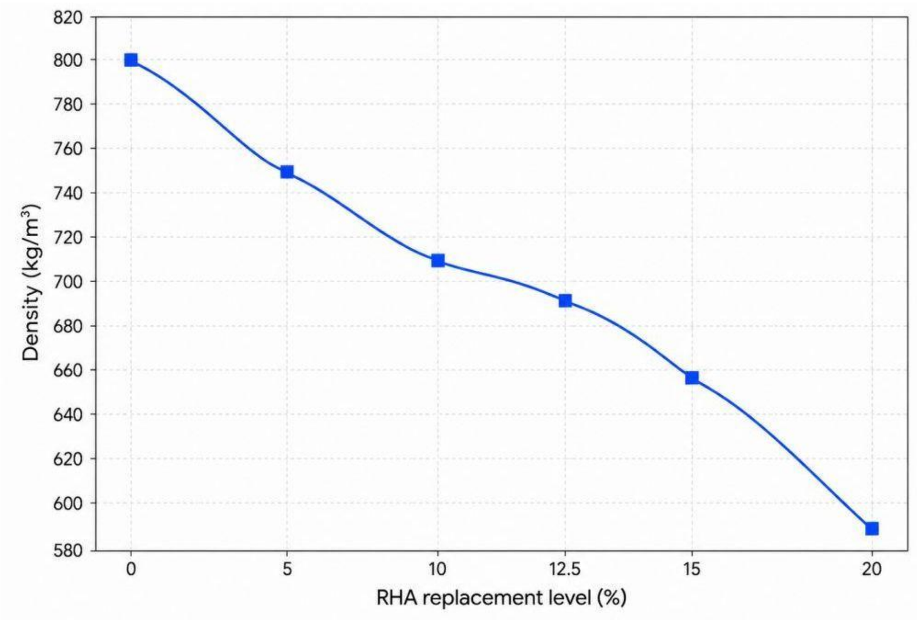

Figure 1 – Effect of RHA replacement level on the bulk density of arbolite composites [Author's material].

The trend also agrees with earlier studies published in the Bulletin of KazGASA on multicomponent arbolite binders, composition optimization, energy-efficient lightweight concrete, and ash-containing building materials [27–30]. Those studies demonstrated the regional feasibility of using agricultural and industrial residues; the present work extends this approach by quantifying the effect of RHA dosage on both mechanical and freeze–thaw performance.

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3.2 Compressive Strength

Compressive strength increased from 3.0 MPa for M0 to 3.5 MPa at 5% RHA and reached 3.8 MPa at 12.5% RHA (Figure 2). The optimum value represents a 26.7% increase relative to the control. The difference of 0.8 MPa is more than four times the maximum observed SD for compressive strength (0.18 MPa), indicating that the improvement was larger than the within-series scatter.

At moderate replacement levels, fine RHA particles can fill voids between cement grains and provide reactive amorphous silica for secondary hydration. These combined microfilling and pozzolanic mechanisms improve continuity of the binder phase around the rice-husk particles. At 15–20% replacement, however, the dilution of Portland cement and the higher surface area and water demand of RHA become dominant; consequently, strength decreased to 3.2 MPa at 20% RHA.

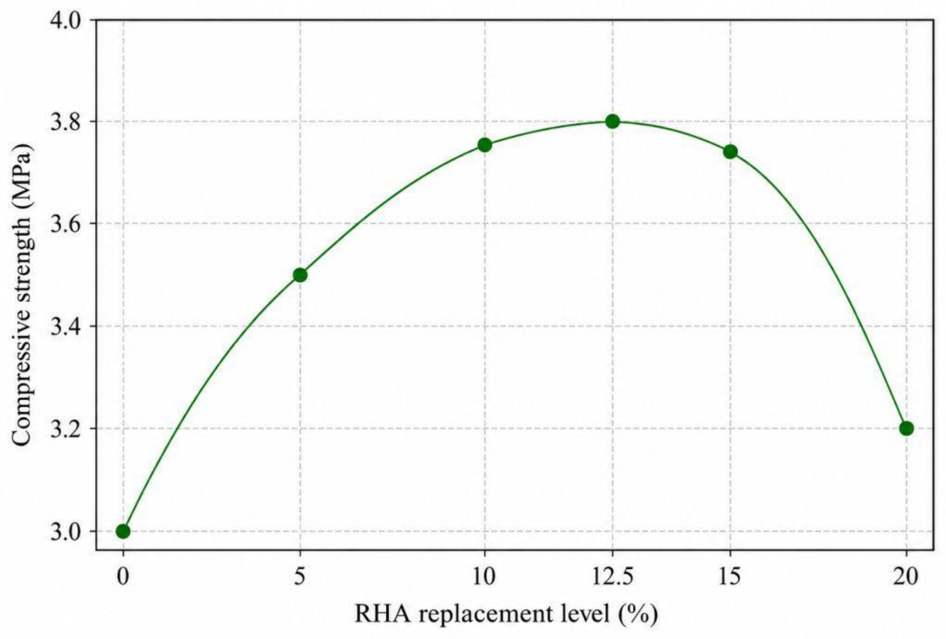

Figure 2 – Effect of RHA replacement level on the compressive strength of arbolite composites [Author's material].

The optimum range determined here is consistent with current international literature. Alsaed and Al Mufti reported that 5–20% RHA could increase concrete strength by approximately 2.4–18.7% depending on age and replacement level [32], while a recent review concluded that the most favorable mechanical and permeability performance is commonly obtained at 10–20% replacement [35]. The larger relative gain observed in the present arbolite (26.7%) should not be interpreted as a direct superiority over conventional concrete, because the control matrix, density, aggregate type, and absolute strength level differ substantially.

Gomes et al. also observed increased compressive strength and lower water absorption in recycled-aggregate concretes containing 10–20% reactive RHA [33]. Similarly, Alharthai et al. obtained their best 28-day performance at 15% RHA in high-recycled-aggregate concrete [36]. These comparisons support the existence of an intermediate optimum but also show that its exact position depends on ash reactivity, fineness, curing, binder content, and the porosity of the aggregate system.

For rice-husk arbolite, the principal contribution of RHA is therefore not merely an increase in absolute compressive strength; it is the partial recovery of matrix integrity in a highly porous composite while maintaining low density. The 12.5% level provided the best compromise among these competing effects.

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The result is also compatible with KazGASA studies on zeolite- and ash-modified cementitious materials, which associate moderate mineral-additive contents with improved particle packing and secondary hydration [26,29].

3.3 Flexural strength

Flexural strength followed the same non-monotonic trend as compressive strength (Figure 3). It increased from 1.0 MPa for M0 to 1.8 MPa for M3 and then decreased to 1.2 MPa for M5. The 0.8 MPa increase at 12.5% RHA is approximately 6.7 times the maximum observed flexural-strength SD (0.12 MPa), which confirms that the change was not explained by specimen-to-specimen scatter alone.

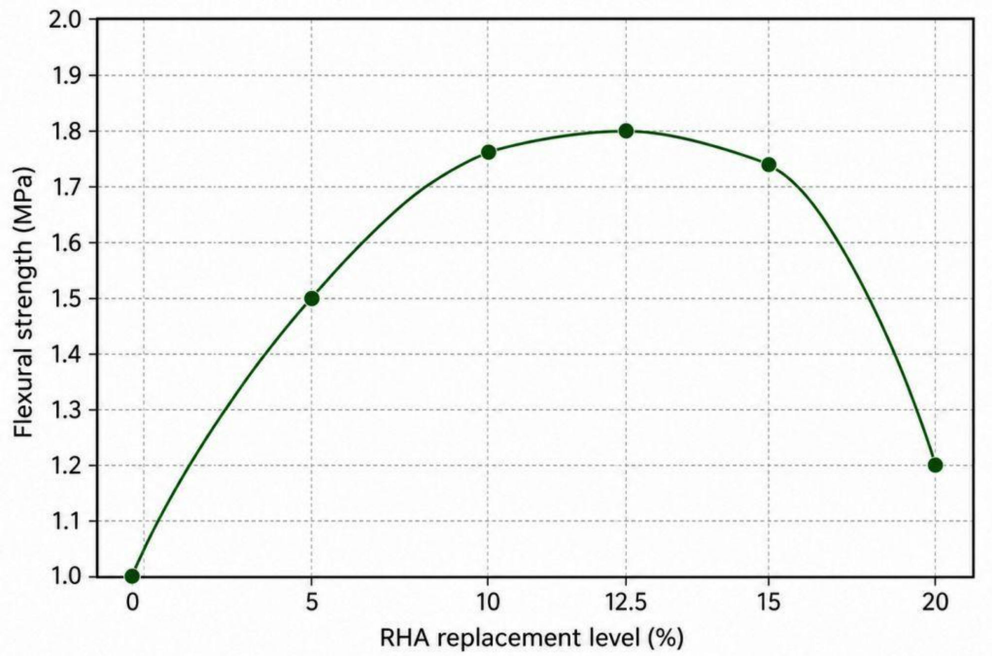

Figure 3 – Effect of RHA replacement level on the flexural strength of arbolite composites [Author's material].

The 80% relative increase reflects the low initial flexural strength of the unmodified arbolite and the sensitivity of crack propagation to the quality of the binder bridges between rice-husk particles.

At the optimum dosage, a more continuous binder phase can improve stress transfer and delay the opening of cracks around the organic filler. The rice husk may also contribute limited crack-bridging and energy dissipation; however, this mechanism was not quantified and should be treated as a plausible interpretation rather than direct proof. The reduction above 12.5% RHA indicates that the benefit of fine-particle filling cannot compensate indefinitely for cement dilution and additional water demand.

3.4 Water absorption

Water absorption decreased from 21.5% for M0 to 17.2% for M3, a reduction of 4.3 percentage points or 20.0% relative to the control (Figure 4). This difference is more than five times the maximum observed SD for water absorption (0.8 percentage points). The decrease up to 12.5% RHA is consistent with improved continuity of the cementitious coating and reduced connectivity of accessible capillary voids. At 15% and 20% RHA, water absorption rose to 19.3% and 23.0%, respectively, showing that excessive replacement increased open porosity and/or reduced the effectiveness of the binder coating.

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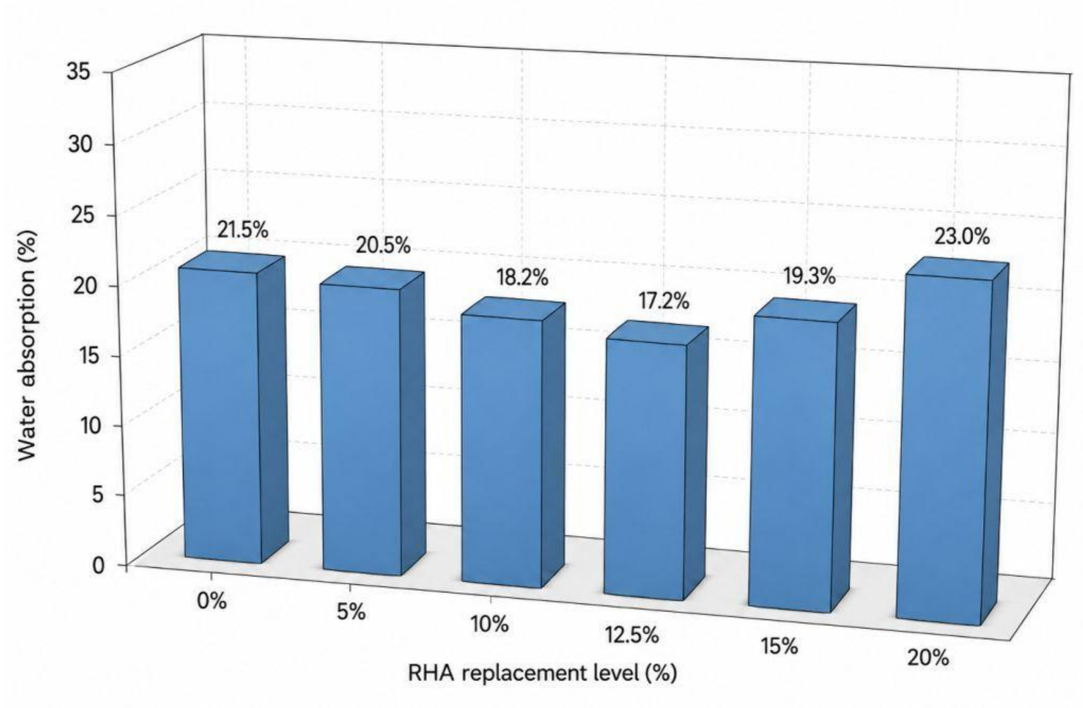

Figure 4 – Effect of RHA replacement level on the water absorption of arbolite composites [Author's material].

The water-absorption trend agrees with the lower absorption reported for RHA-modified recycled concrete by Gomes et al. [33] and with the broader durability mechanisms summarized by Guo et al. [35]. Nevertheless, the minimum value of 17.2% remains high compared with dense conventional concrete because rice husk is intrinsically porous and hydrophilic. Therefore, the result should be interpreted as improved water resistance relative to the control, not as complete waterproofing. Exterior use requires moisture-protective rendering, coating, or cladding, and future work should determine the softening coefficient, sorptivity, and behavior under prolonged wetting–drying cycles.

3.5 Frost resistance and durability performance

Table 3. Frost resistance coefficients of arbolite composites after freeze–thaw cycling [Author's material].

Mix ID	W/B	After 15 cycles	After 25 cycles	After 35 cycles
M0	0.50	0.61	0.34	–
M1	0.50	0.88	0.69	0.51
M2	0.50	0.90	0.80	0.62
M3	0.50	0.92	0.83	0.65
M4	0.50	0.82	0.70	0.56
M5	0.50	0.80	0.68	0.51

Note: The frost resistance coefficient (Kfr) was calculated as the ratio of residual compressive strength after freeze–thaw cycling to the initial compressive strength. The dash indicates that the M0 specimens did not retain structural integrity after 35 cycles and that no valid coefficient could be determined.

Freeze–thaw resistance is critical for lightweight bio-aggregate materials used in the continental climate of Kazakhstan. As shown in Table 3, all RHA-containing mixtures retained a greater proportion of their initial compressive strength than M0 at each test stage. The optimum M3 composition combined the lowest water absorption with the highest residual-strength coefficients, providing a coherent relationship between moisture uptake and cyclic freezing damage.

After 15 cycles, Kfr was 0.92 for M3 compared with 0.61 for M0; after 25 cycles the corresponding values were 0.83 and 0.34. Thus, the relative advantage of M3 increased as exposure

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progressed. After 35 cycles, M3 retained Kfr = 0.65, whereas the control specimens no longer retained sufficient structural integrity for a valid strength determination. The data demonstrate improved resistance to the adopted laboratory regime, but they do not justify assigning a standard frost-resistance grade without the acceptance criteria and full test program required by the relevant product standard.

The probable mechanism is a reduction in the amount and connectivity of freezable water in the optimized binder phase. A more continuous coating around rice-husk particles limits local water accumulation, thereby reducing hydraulic and crystallization pressures during freezing. This interpretation is supported by the simultaneous minimum in water absorption at 12.5% RHA, although quantitative porosimetry would be necessary for direct confirmation.

From a practical standpoint, the material may be used in non-load-bearing wall blocks and partition elements exposed to moderate seasonal temperature variations, provided that direct water penetration is prevented. Before exterior application, testing should be extended to a larger number of cycles, wetting–drying exposure, dimensional stability, biological resistance, thermal conductivity, and full-scale wall elements.

3.6 Microstructural observations

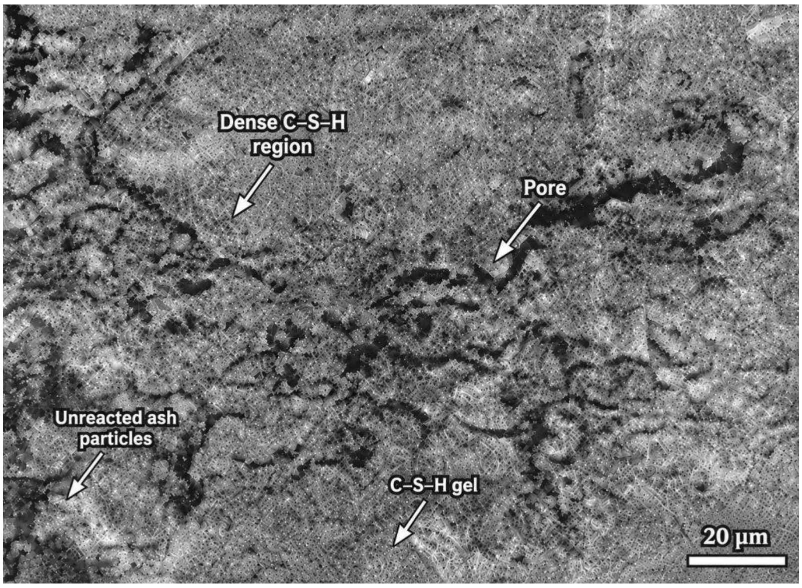

Figure 5 – Microstructure of the hardened binder matrix containing 12.5% rice husk ash obtained by transmission electron microscopy (EMV-100BR, ×2400; scale bar = 20 µm). Arrows indicate morphologically interpreted zones; phase identification is tentative in the absence of EDS/XRD confirmation [Author’s material].

Figure 5 contains a 20 µm scale bar and marks the principal zones considered during qualitative interpretation: relatively compact matrix regions, visible pores, and possible residual ash particles. The image shows that dense and porous regions coexist within the optimized binder. This heterogeneity is expected in arbolite because the cementitious phase develops around a highly porous organic filler.

The comparatively compact areas are consistent with the increases in compressive and flexural strength and with the lower water absorption of M3. Finely ground RHA is widely reported to act as a microfiller and, where sufficient amorphous silica is present, to participate in pozzolanic reactions [8,10,12,21,35]. However, morphology alone cannot prove the presence of C–S–H or quantify pore refinement. Accordingly, the labels in the micrograph should be understood as tentative morphological interpretations, and future work should include a control micrograph, EDS mapping, XRD, and quantitative pore analysis.

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The deterioration of strength and water absorption at 20% RHA confirms that microstructural improvement is dosage-dependent. Above the optimum, reduced clinker content and increased water demand can produce insufficiently bonded or more porous regions, offsetting the benefits of ash fineness and secondary hydration.

3.7 Comparison with recent studies and practical implications

Table 4 compares the present results with recent studies published in 2023–2025. Direct numerical comparison must be made cautiously because conventional concrete, recycled-aggregate concrete, and rice-husk agro-concrete belong to different density and strength classes. Nevertheless, the studies consistently identify a moderate RHA content as beneficial and excessive replacement as potentially unfavorable.

Table 4 – Comparison of the present results with recent studies published in 2023–2025

Study	Material and dosage	Main finding	Relation to the present study
Alsaed and Al Mufti [32]	Conventional concrete; 5–20% RHA	Strength gains of approximately 2.4–18.7%, depending on age and dosage	Supports a beneficial intermediate replacement range
Gomes et al. [33]	Recycled-aggregate concrete; 10–20% RHA	Higher strength and lower water absorption with reactive RHA	Consistent with simultaneous strength increase and absorption reduction
Rodríguez Neira et al. [34]	Rice-husk insulation panel produced by a pulping method	Thermal conductivity of 0.037–0.042 W/(m·K); water and acoustic performance also characterized	Confirms the suitability of rice husk for lightweight non-load-bearing building products, but is not used for direct strength comparison
Guo et al. [35]	Review of RHA cement-based materials; commonly 10–20%	Moderate RHA contents improve mechanical and permeability-related properties	Supports the 12.5% optimum and the proposed mechanisms
Alharthai et al. [36]	High recycled-aggregate concrete; 5–20% RHA	Best 28-day performance at 15% RHA	Shows that the exact optimum is system-dependent but lies in a comparable range
Present study	Rice-husk arbolite; 0–20% RHA	Optimum at 12.5%: 3.8 MPa, 1.8 MPa, 17.2% absorption, Kfr = 0.65 after 35 cycles	Extends recent research by combining mechanical, moisture, freeze–thaw, and microstructural evaluation

Previous regional studies have demonstrated the effectiveness of multicomponent binders, ash-based additives, and mathematical optimization in improving the properties of lightweight cementitious composites and arbolite materials [26–30]. Recent international investigations have similarly confirmed that the incorporation of rice husk ash and other supplementary cementitious materials can enhance strength, reduce water absorption, and improve the durability-related performance of cement-based composites when an optimal replacement level is selected [31–36].

The recommended field of application is non-load-bearing lightweight wall and partition products. The reduced density can lower dead load, while the strength values are appropriate for selected non-structural products. Because water absorption remains 17.2% even in M3, exterior products require a protective surface system. The present findings are therefore a basis for product development rather than a final declaration of universal service suitability.

The principal limitations of the present work are the small number of specimens per series (n = 3), the qualitative nature of microscopy, the absence of a control micrograph and quantitative pore

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analysis, and the freeze–thaw limit of 35 cycles. These limitations are explicitly considered in the interpretation and define the next stage of verification.

4 CONCLUSIONS

The effect of replacing 0–20% of Portland cement with rice husk ash was evaluated in rice-husk-based arbolite using density, mechanical strength, water absorption, freeze–thaw resistance, and qualitative microscopy. All reported physical and mechanical results represent the mean of three specimens, with the observed scatter summarized by standard deviations and coefficients of variation. The main conclusions are as follows:

1. Partial replacement of Portland cement with RHA reduced the bulk density from 800 kg/m³ for M0 to 590 kg/m³ for M5. The magnitude of this change substantially exceeded the observed density scatter, and all compositions remained within the lightweight-material range.
2. The most favorable mechanical performance was obtained for M3 containing 12.5% RHA. Compressive strength increased from 3.0 to 3.8 MPa (26.7%), and flexural strength increased from 1.0 to 1.8 MPa (80%). Both increases were several times greater than the maximum observed SD for the corresponding property.
3. Water absorption decreased from 21.5% for M0 to 17.2% for M3, corresponding to a 20.0% relative reduction. Further replacement increased water absorption to 19.3% at 15% RHA and 23.0% at 20% RHA, confirming the dosage-dependent character of the effect.
4. M3 exhibited the highest resistance to the adopted freeze–thaw regime, with coefficients of 0.92, 0.83, and 0.65 after 15, 25, and 35 cycles, respectively. The control mixture reached 0.61 and 0.34 after 15 and 25 cycles and lost structural integrity before completion of 35 cycles.
5. The micrograph of M3 showed comparatively compact and porous regions within the hardened binder matrix. This qualitative observation is consistent with the performance trends but does not independently prove phase composition or quantitative pore refinement; EDS/XRD and porosimetry are required for confirmation.

Overall, 12.5% RHA provided the most favorable balance of density, strength, water absorption, and resistance to the adopted freeze–thaw regime. The scientific contribution is the identification of this multi-criterion optimum for a composite containing both rice husk and RHA. The material is recommended for further development as non-load-bearing wall and partition products, with moisture-protective finishing for exterior service. Future work should increase the number of specimens, extend freeze–thaw and wetting–drying exposure, quantify pore structure, determine thermal conductivity and biological resistance, and test full-scale elements.

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Nauryzbay Alibekov – methodology, investigation, preparation of the experimental mixtures, validation of the test results, and provision of research resources.
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