

LIGHTWEIGHT CONCRETE FOR MODULAR CONSTRUCTION: STRENGTH, DENSITY AND MICROSTRUCTURAL PERFORMANCE AT LABORATORY AND PRODUCTION SCALES

Aigerim Tolegenova¹, Teshev Iliia^{1,2}, Yuri Shchedrin², Murat Tamov³, Alexander Savin², Nikita Volkov⁴,
Zauresh Zhambakina¹ and Adlet Zhagifarov^{1*}

¹Department of Civil Engineering and Building Materials, Satbayev University, Kazakhstan; ²MX Innovation LLP, Astana, Kazakhstan; ³Kuban State Technological University, Krasnodar, Russian Federation; ⁴ModeX HBP (BI Group), Astana, Kazakhstan.

*Corresponding Author, Received: 09 Nov. 2025, Revised: 19 Jan. 2026, Accepted: 30 Jan. 2026

ABSTRACT: The performance of lightweight structural concrete with porous aggregates (LWPA) in precast and modular construction is strongly influenced by aggregate grading and curing conditions; however, the comparative effects of different expanded clay aggregate fractions under production-orientated conditions remain unstudied enough. This study evaluates the influence of 5–8 mm and 5–10 mm expanded clay aggregate fractions on the physical, mechanical, and microstructural properties of LWPA at both the laboratory and production scales. The density, compressive strength, and workability were measured. Following laboratory validation, full-scale wall panels and volumetric blocks were produced and tested under production conditions. Microstructural features were investigated using XRD, SEM, and EDS. The results showed that at 28 days, the concrete produced with the 5–10 mm expanded clay aggregate fraction exhibited a 12.3 to 12.8% higher compressive strength than mixes with the 5–8 mm fraction, depending on the mixture type. The density of the mixtures ranged from 1867 to 1912 kg/m³, meeting LWPA requirements. Microstructural analysis confirmed enhanced hydration and a denser cement matrix in the experimental mixtures. The findings demonstrate that optimized expanded clay aggregate grading provides an effective balance among strength, density, and technological performance, supporting the production of prefabricated wall panels and volumetric blocks for sustainable and modular construction.

Keywords: Lightweight concrete, Expanded clay aggregate, Prefabricated wall panel, Volumetric block, Compressive strength.

1. INTRODUCTION

Lightweight concretes with porous aggregates (LWPA) have attracted increasing attention for their lower density, improved thermal insulation, and relevance to sustainable and energy-efficient construction [1–3]. Their use reduces structural self-weight, foundation loads, and reinforcement requirements [4–6], which is particularly important for prefabricated, modular, and high-rise buildings [7–9]. Consequently, lightweight concrete is widely used in wall panels, facade elements, and volumetric blocks, where an optimal balance between strength and low density is essential for efficient transportation and assembly.

Among lightweight aggregates, expanded clay is among the most widely used due to its availability, relatively low cost, and favourable mechanical and thermal properties [10–12]. In recent years, research has also examined the incorporation of recycled materials and industrial by-products to improve the sustainability of lightweight concretes and reduce resource consumption [13–20]. These studies confirm that expanded clay-based concretes can be effectively adapted for both structural and non-structural applications, particularly in low-carbon and prefabricated construction systems.

The particle-size distribution and classification of lightweight aggregates are widely recognized as key parameters governing the mechanical and physical performance of lightweight concrete. Numerous studies have shown that aggregate classification directly affects compressive strength, stiffness, fracture behavior, and overall structural performance, mainly by influencing particle packing and stress transfer within the cementitious matrix [21,22]. Specifically, denser particle packing has been associated with higher load-bearing capacity and reduced stress concentrations at the aggregate–paste interface.

In particular, finer aggregate fractions have been reported to improve packing density and interfacial bonding, resulting in improved compressive strength and fewer internal defects under controlled laboratory conditions [23,25]. These effects are commonly attributed to improved matrix continuity, lower void content, and more uniform stress distribution within the hardened composite. Aggregate grading also plays a crucial role in the regulation of fresh-state behavior and mixture stability. Optimized particle-size distribution has been shown to reduce segregation, improve workability, and promote more homogeneous compaction, especially in lightweight concretes containing porous aggregates with high

water absorption [22,24,26]. Experimental results indicate that balanced classification supports stable rheological behavior and minimizes bleeding and floating aggregate during placement.

In contrast, coarser lightweight aggregate fractions, while reducing density, can increase internal porosity and lead to less uniform stress distribution, potentially limiting mechanical performance if not properly compensated for by mixing design adjustments [25,29,30]. In such cases, reductions in compressive strength have been associated with increased pore connectivity and weaker interfacial transition zones.

Beyond macroscopic properties, the aggregate size distribution also influences microstructural development, particularly in the interfacial transition zone (ITZ). Several studies have shown that smaller, well-graded expanded clay aggregates promote a denser ITZ and improved paste–aggregate bonding, while larger particles may introduce localized stress concentrations and microstructural discontinuities [29,30,37]. These microstructural differences directly affect the crack initiation paths and the progression of microcracks under mechanical loading. Microstructural investigations using SEM, XRF, and EDS have also confirmed that aggregate grading affects hydration products, pore structure, and crack-initiation mechanisms in lightweight concrete systems [37–40]. In particular, variations in aggregate size have been shown to influence C–S–H morphology, calcium-to-silicon ratios in the cement matrix, and the spatial distribution of pores at the microscale.

Despite the extensive body of literature on lightweight concretes that incorporate expanded clay aggregates [42–44,50], important research gaps persist. Most prior studies have focused on laboratory-scale specimens and non-structural applications, with limited attention to industrial curing regimes and full-scale production conditions [28,30,48]. Consequently, the applicability of many of the reported findings to real-world production environments remains uncertain.

In particular, the comparative effects of commonly used expanded clay aggregate fractions, such as 5–8 mm and 5–10 mm, on strength, density, workability, and microstructural development under accelerated steam curing have not been systematically investigated. This lack of comparative data limits the development of evidence-based mixture design recommendations for prefabricated wall panels and modular volumetric construction. Moreover, experimental evidence linking laboratory observations to production-scale elements, such as prefabricated wall panels and volumetric modular blocks, remains scarce.

Consequently, this study addresses these gaps by providing a systematic evaluation of how the grading of the expanded clay aggregate affects the strength,

density, and microstructural characteristics of lightweight concrete. The analysis is supported by XRD, SEM, and EDS investigations and validated through both laboratory-scale testing and production-scale implementation under industrial curing conditions relevant to modular construction applications.

2. RESEARCH SIGNIFICANCE

This research aims to optimize lightweight structural concrete for precast and modular construction by systematically evaluating the effect of the size of the expanded clay aggregate on both both laboratory and production scales. Unlike most previous studies limited to laboratory testing, this work establishes a clear link between aggregate classification, early-age strength development kinetics, density evolution, and microstructural formation under accelerated curing conditions. The combined use of XRD, SEM and EDS analyses, together with the production of full-scale wall panels and volumetric blocks, demonstrates the practical applicability and scalability of the proposed concrete compositions. The findings provide engineering-orientated guidelines for mixture design and lay a foundation for further research on the strength, density, and microstructure of lightweight concrete on both laboratory and production scales.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Raw materials

Portland cement CEM I 42.5 H, commercially produced by Central Asian Cement JSC (Kazakhstan) and according to ST RK 31108-2020 “Cements. General Technical Specifications” was used as the binder. Construction sand (0/3.2mm fraction, bulk density 1637 kg/m³) from the Kyzylzhar village (Akmolinsk region, Kazakhstan) served as fine aggregate. The particle-size distribution of the sand is shown in Fig. 1.

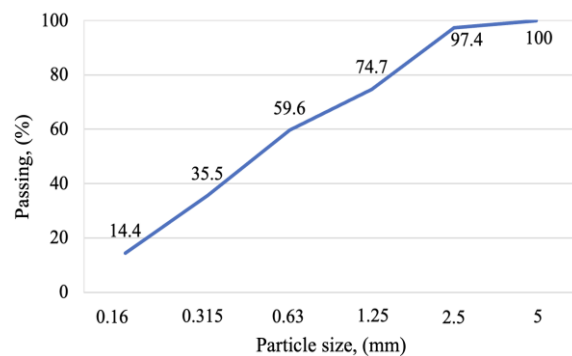


Fig. 1 Particle size distribution of sand

Expanded clay aggregate with particle sizes of 5–8 mm (Taldykorgan, Kazakhstan) and 5–10 mm (Tyumen region, Russia) was used as a lightweight porous aggregate (Fig. 2). The bulk density of the aggregates was 530 kg/m³ and 510 kg/m³, respectively, according to ST RK 32496-2013 “Lightweight aggregates for concrete. Technical specifications”. The granulometric compositions of the expanded clay fractions are presented in Table 1, while their general physical properties are summarised in Table 2.

Table 1. Granulometric composition of the expanded clay aggregates.

No	Particle size, mm	Full residual of fraction 5-10 mm, %	Full residual of fraction 5-8, %
1	10	22.55	3.5
2	7.5	45.9	67.2
3	5	69.75	97.85
4	<5	100	100

Table 2. General properties of lightweight expanded clay aggregates.

No	Properties	Expanded clay, 5-8 mm	Expanded clay, 5-10 mm
1	Grade by bulk density	M500	M500
2	Compressive strength, MPa	3.55	3.18
3	Grade by crushing capacity	P150	P150
4	Water absorption, %	16	21



Fig. 2. Expanded clay aggregate

3.1.2 Chemical admixtures

A polycarboxylate ether-based superplasticizer (MC-Powerflow 7951N, MC-Bauchemie) was incorporated to enhance the workability of the mixes. The PCE dosage was kept constant at 1.0% by weight of cement across all mixtures, consistent with the values reported in Tables 3 and 4. The superplasticizer was used to ensure stable workability, prevent segregation of the lightweight concrete mixtures, and maintain comparable fresh-state conditions when assessing the influence of aggregate fraction on early-age and ultimate strength

development.

3.2 Methods

3.2.1 Mix proportion

All specimens contained 1% polycarboxylate ether (PCE) by mass of cement. This approach was chosen to evaluate the effects of expanded clay aggregate particle size and chemical admixture on the workability, density, and strength of lightweight concrete. The detailed mixture proportions are presented in Tables 3 and 4.

Table 3. Compositions of an expanded clay concrete mixture with a fraction 5–8 mm

No	Cement, kg	Sand, kg	Expanded clay aggregate, kg	Water, kg	PCE, kg
M1	410	1200	280	201	4.2
M2	410	1150	275	190	4.1

Table 4. Compositions of an expanded clay concrete mixture with a fraction 5–10 mm

No	Cement, kg	Sand, kg	Expanded clay aggregate, kg	Water, kg	PCE, kg
M3	430	1060	280	203	4.3
M4	430	1120	275	192	4.3

Note: M1 –control composition (5–8 mm); M2 –experimental composition (5–8 mm); M3 –control composition (5–10 mm); M4 –experimental composition (5–10 mm).

Water refers to total mixing water; minor adjustments were made to the sand and water to meet the target workability/stability, considering LECA absorption.

The mixing procedure was carried out according to EN 206:2013 “Concrete – Specification, performance, production and conformity”. First, dry components (sand and expanded clay aggregate) were weighed and premixed to ensure a uniform distribution. Then, cement was introduced, followed by additional mixing to obtain a homogeneous binder matrix. In the final stage, water and chemical admixtures were added to achieve the required rheological properties and stability of the mix. Sand and expanded clay aggregates were used as supplied, without oven drying or saturated surface-dry (SSD) conditioning.

The water used to mix corresponds to the total water added to the mixture. Initially, the mixture was tested on laboratory specimens (100×100×100 mm) to determine the compressive strength at 1, 7, and 28 days. The compressive strength of concrete cube specimens was determined according to GOST 10180–2012 “Concretes. Methods for strength determination using reference specimens”. Cube specimens were used throughout the study; therefore, no strength conversion factors were applied. At each test age, the compressive strength was determined from three cube specimens (n = 3), and the results are reported as mean values with standard deviation (±

SD). Subsequently, the same lightweight concrete mix was used to cast a full-scale modular block. To verify strength and density, companion cube specimens were cast simultaneously with the block and tested at 1, 7, and 14 days.

3.2.2 Workability, specimen preparation and strength testing

The workability of fresh concrete mixes was evaluated using the Abrams cone slump test (EN 12350-2:2019). A 26 cm slump was measured immediately after mixing. Additional observations were made over 60 minutes after mixing, during which no visible segregation or bleeding was observed. The high slump was achieved through optimized aggregate grading and the use of a polycarboxylate ether-based superplasticizer.

The cube specimens were cast from the prepared mixes and cured. Accelerated curing was performed in a KUP-1 steam chamber under a controlled regime: (i) heating for 1.5 h, corresponding to an average temperature ramp rate of approximately 40–45 °C/h, until the chamber temperature reached 65 °C; (ii) isothermal holding at 65 °C for 4.5 h; and (iii) controlled cooling to 30 °C within 1.5 h. The specimens were exposed to a high-humidity environment provided by saturated steam and were not sealed during curing. This curing regime was selected to simulate typical factory-based accelerated curing conditions for prefabricated concrete elements, ensuring uniform heat distribution and promoting accelerated hydration and early strength gain without causing thermal damage. After steam curing, all specimens were stored under standard laboratory conditions (20 ± 2 °C, 95% RH) until testing.

In addition to laboratory specimens, full-scale wall panels were manufactured from lightweight expanded clay concrete with a 5–10 mm aggregate fraction. The panels were cast under production conditions using standard formwork and curing procedures. These pilot elements were prepared to evaluate the technological properties of the mixes developed in real production, including workability, product surface quality, and suitability for large-scale casting. Furthermore, the panels were used to verify the structural and thermal performance of the material under practical operating conditions.

To further assess the strength development of the experimental mixes, a volumetric block BU 58.29-3.2-02B was cast using the M3 and M4 specimens (Fig. 3). A volumetric block is a large structural element manufactured in a factory to be used to build residential and public buildings. It is a three-dimensional module, such as a wall block, and can be used as part of a larger module [11].

The block exhibited a satisfactory external appearance, with no visual defects or deviations observed during the transition to the experimental mix. This allowed not only confirmation of the

applicability of the mix for large structural elements but also monitoring of the kinetics of strength gain under production conditions. The configuration of the full-scale volumetric block and the testing setup are illustrated in Fig. 3.

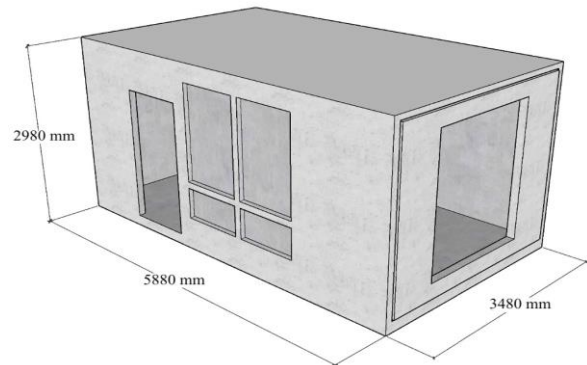


Fig. 3. 3D model of a full-scale volumetric concrete block used in the study.

3.2.3 Production Casting of Full-Scale Elements

After laboratory validation of the concrete mixtures, the full-scale elements were produced under production conditions. The concrete was poured at 1.8 m³ per batch using a planetary-type mixing plant. The casting was performed in panel and volumetric block formwork. Compaction was achieved using vibrators mounted on an external formwork operating at 50 Hz with an amplitude of approximately 200 μm. The vibrators were activated every 10 s for 5 s throughout the casting process to ensure uniform compaction.

Steam curing was applied after production casting: the temperature was increased to 80 °C in 1 h, maintained at 80 °C for 3.5 h, and then reduced to 50 °C in 0.5 h. After demolding, the surface quality of the elements was visually inspected.

3.2.4 X-ray Diffraction (XRD)

The phase composition of the powdered concrete samples at 28 days was analyzed using a DRON-3 diffractometer with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) and a β operating at 35 kV and 20 mA. The samples were obtained from small concrete fragments (approximately 1–2 cm) extracted from cube specimens after compressive strength testing, then dried under laboratory conditions, mechanically ground, and sieved to pass a 200-mesh size. Scans were recorded in a 2θ range of 5 to 70° with a step size of 0.02° and a scanning rate of 2°/min. No chemical treatment was applied prior to XRD analysis.

3.2.5 Scanning Electron Microscopy (SEM) and Energy-Dispersive Spectroscopy (EDS)

The microstructure of hardened lightweight concrete samples at 28 days was examined using a scanning electron microscope (SEM) operating at an accelerating voltage of 10 kV, with a working

distance of 14 mm in high-vacuum mode. The images were captured at magnifications of $\times 2000$ and $\times 3000$, focussing on the morphology of the hydration products and the interfacial transition zones (ITZ) between the cement matrix and expanded clay aggregates of fractions 5–8 mm (M1) and 5–10 mm (M4).

Small concrete fragments, approximately 1–2 cm in size, were extracted from $100 \times 100 \times 100$ mm cube specimens after compressive strength testing, using fractured surfaces formed during loading. No chemical treatment was applied to the samples. Before analysis, loose dust was removed with compressed air and the specimens mounted on metallic holders for SEM observation.

In addition to SEM imaging, energy-dispersive X-ray spectroscopy (EDS) was performed on selected areas to qualitatively assess the elemental composition and spatial distribution of the main elements within the cement matrix and ITZ. EDS elemental maps and spectra were collected under the same operating conditions as SEM observations. The EDS analysis supported microstructural interpretation; quantitative elemental analysis was not the primary objective, and the results are discussed qualitatively.

4. RESULTS AND DISCUSSION

4.1 Effect of Aggregate Particle Size on Density and Compressive Strength

After one day of steam curing, all specimens exhibited densities of 1875–1964 kg/m^3 and compressive strengths of 21–24 MPa, indicating rapid early strength gain, as shown in Fig. 4. On day 7, the density decreased slightly to 1836–1947 kg/m^3 due to partial moisture loss, while the compressive strength increased significantly to 25–30 MPa. After 28 days, the density of the concrete stabilized between 1820 and 1920 kg/m^3 , and the compressive strength increased further to 28.8 to 34.5 MPa, confirming the effectiveness of the curing regime in promoting the continued development of the strength. Although the hardened density of the 5–10 mm expanded clay aggregate fraction was higher than that of the 5–8 mm fraction, the resulting concrete had a lower overall density. This reduction can be attributed to the more porous internal structure and the looser packing of the larger aggregate, which generated additional voids within the matrix.

The aggregate packing density and the void ratio were not experimentally determined in this study; therefore, the observed density behavior is interpreted using the particle size distribution data (Table 1) and the intrinsic porosity of the expanded clay aggregates.

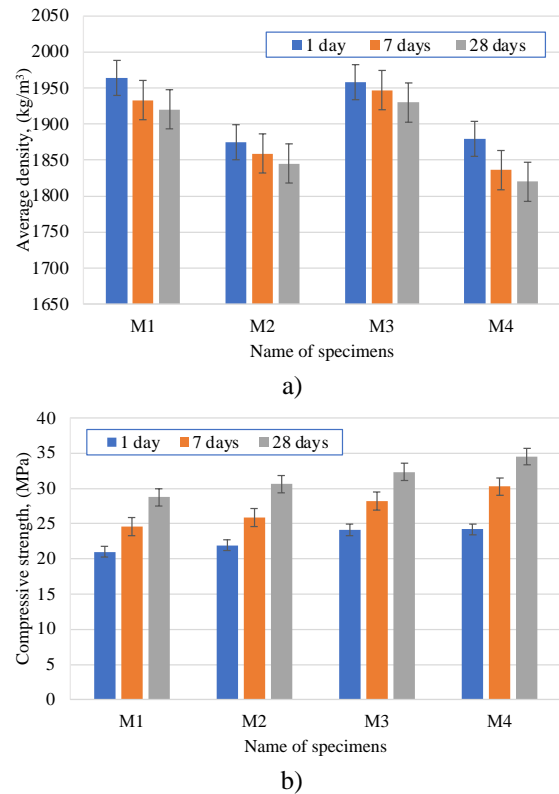


Fig. 4. Density and compressive strength of control and experimental lightweight concretes after steam curing: a) average density; b) compressive strength

During production tests, wall panels were first cast using lightweight expanded clay concrete with a 5–10 mm aggregate fraction. The panels exhibited good workability and high surface quality, confirming the suitability of the experimental mix for industrial application. Subsequently, a full-scale volumetric block was cast from the same experimental specimen M4. The block showed a uniform surface without visible defects or irregularities, indicating that the transition to the experimental composition did not negatively affect the technological quality of the elements. The production and large-scale testing of lightweight expanded clay concrete elements are illustrated in Fig. 5. The figure presents the main technological stages, including the casting process, surface evaluation, and load testing of prefabricated components. The visual results confirm the satisfactory workability and surface finish of the concrete mix, as well as its structural integrity during testing. Additionally, the experimental compositions demonstrated stable performance in the production of prefabricated wall panels and volumetric blocks, confirming their suitability for modular construction applications.

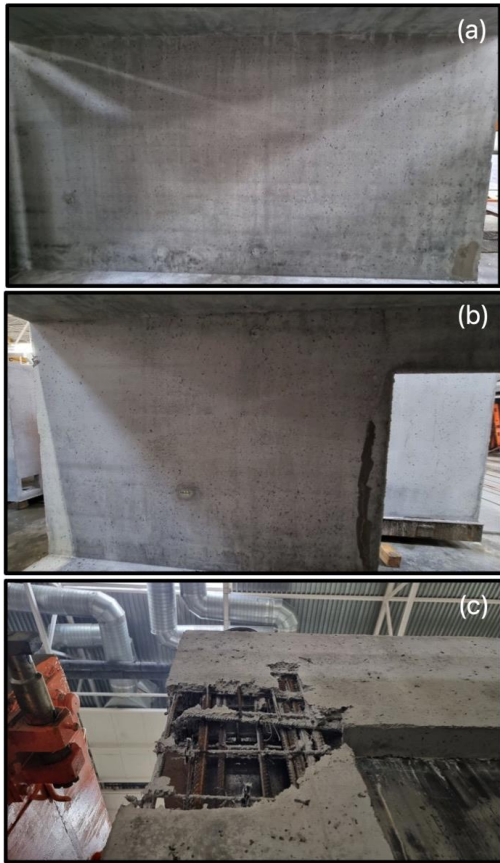


Fig. 5. Production and testing of full-scale lightweight expanded clay concrete elements: (a) surface quality of the panel after demoulding; (b) volumetric block with integrated wall and opening, produced from the experimental mix M4; (c) fragment of the volumetric block after mechanical testing, showing the reinforcement exposure and the fracture surface

In this study, no mechanical testing of full-scale volumetric blocks was conducted; however, the failure modes and stress distribution of similar modular blocks have been analyzed in previous work of the authors' [7, 11], providing a basis for interpreting the structural behavior of the elements produced.

The concrete strength of the wall panel was evaluated using companion cube specimens ($100 \times 100 \times 100$ mm) prepared from the same mix and cured under identical steam treatment conditions. At demoulding, the strength reached 16.2 MPa (62% of design strength), increasing to 21.5 MPa after 1 day and 25.4 MPa after 3 days, corresponding to 82% and 97% of the design strength, respectively. These results indicate rapid early-strength development, confirming the suitability of the mix for prefabricated wall production, as shown in Fig. 6.

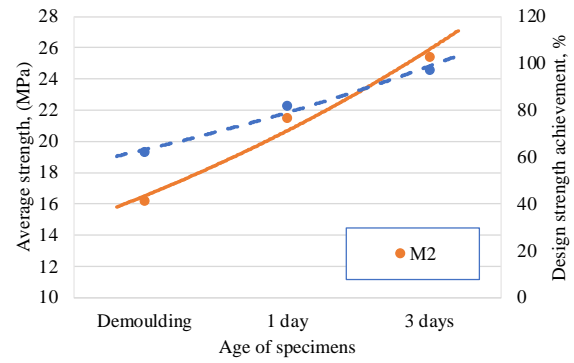
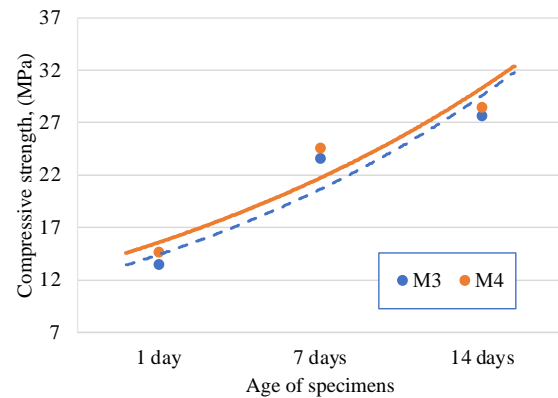
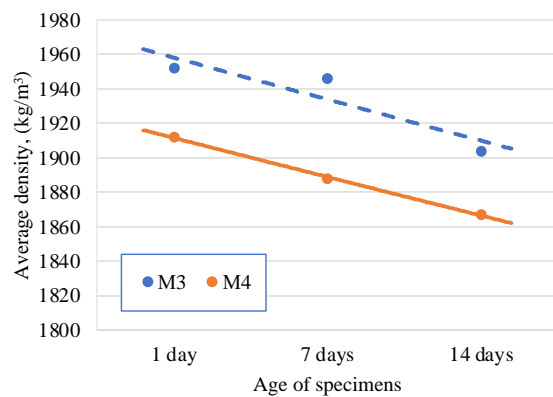


Fig. 6. Compressive strength of lightweight expanded clay concrete under steam curing

In addition, companion cube specimens ($100 \times 100 \times 100$ mm) were tested to verify strength and density. Figure 7 shows that after 1 day, the experimental cubes reached a density of 1912 kg/m^3 and a strength of 14.62 MPa, slightly higher than the control specimen (13.47 MPa at 1952 kg/m^3). At 7 days, the experimental mix M4 reached 24.63 MPa, compared to 23.61 MPa for the control M3, and after 14 days it reached 28.47 MPa, compared to 27.68 MPa for the control. The density of both experimental and control specimens decreased slightly over time due to moisture loss, but the development of the strength remained consistent.



a)



b)

Fig. 7. Development of the strength (a) and density (b) of lightweight expanded clay concrete

This additional testing was conducted to ensure that the concrete's mechanical performance remained stable when used in full-scale modular elements. The results confirmed the reliability of the designed mix under practical casting conditions. The revealed patterns correspond with data from previous studies on lightweight concretes based on porous aggregates.

In [14] it was reported that smaller aggregate fractions provide increased density and hardness due to a denser packing, consistent with the data obtained for concrete with expanded clay of 5-8 mm. Researchers [15], in contrast, observed a decrease in strength with increasing particle size, which explains the slightly lower density of concrete containing expanded clay particles of 5–10 mm.

Despite the observed variation in the average density between M3 and M4, their compressive strength remained comparable between all curing ages. This can be explained by the fact that strength development in lightweight concrete is more strongly influenced by cement hydration, secondary C–S–H formation, and ITZ quality than by density alone. Differences in density are mainly related to aggregate porosity and packing, which affect bulk density but do not necessarily reduce load-bearing capacity when the cementitious matrix is well developed. Similar behavior has been reported in previous studies (e.g., [16]).

Nevertheless, optimizing the composition allowed maintaining or even exceeding strength values compared to control samples. This is consistent with conclusions by Chung et al., who emphasized the crucial role of the granulometric composition in preventing delamination and ensuring a uniform structure. Furthermore, previous work [17-18] showed that porosity and the distribution of aggregate fractions significantly affect water absorption and durability. This confirms the interpretation of the differences between the expanded clay concrete of 5-8 mm and the expanded clay concrete of 5-10 mm identified in this study.

Along with confirming well-known scientific patterns, the results of this study have significant practical importance for pre-fabricated and modular housing construction. Rapid strength gain (more than 60% of design strength at demolding and almost 100% within three days) is particularly valuable for industrial production, as it accelerates mold turnover and shortens the heat treatment cycle. Reference [11] reached similar conclusions, noting that early durability is a key factor in improving modular housing production efficiency. Thus, the developed compositions not only confirm patterns identified in previous studies but also extend their application to large-scale manufacturing of wall panels and blocks, underscoring their technological and practical significance for sustainable construction.

4.2 Phase Composition Analysis (XRD)

Fig. 8 shows the XRD patterns of lightweight concrete specimens containing expanded clay aggregates of 5–8 mm (M1) and 5–10 mm (M4). Both compositions show diffraction peaks of quartz (SiO_2) and portlandite ($\text{Ca}(\text{OH})_2$), along with traces of feldspars (albite and K-feldspar) and vesuvianite, associated with the aluminosilicate structure of the expanded clay. The dominant diffraction peak at $2\theta \approx 26.6^\circ$ corresponds to quartz (SiO_2), indicating that the silica phases of the sand and expanded clay aggregates prevail in both mixtures. The identified quartz is a crystalline phase that originates primarily from sand and expanded clay aggregates.

A reduced intensity of portlandite reflections was observed at $2\theta \approx 18^\circ$ and 34° in the experimental mix, indicating a higher degree of hydration and partial consumption of $\text{Ca}(\text{OH})_2$ in pozzolanic reactions involving amorphous silica, which is not detected directly as a crystalline phase by XRD. The higher content of quartz and vesuvianite (35.2% and 12.8%) suggests enhanced secondary C–S–H formation, correlating with improved mechanical properties. In contrast, the control mix (5–8 mm) showed higher portlandite and calcite contents (18.9% and 7.7%), reflecting slightly lower reactivity and a denser but less hydrated cement matrix.

These findings confirm that increasing the aggregate fraction to 5–10 mm results in a more balanced hydration process, while quartz remains the dominant crystalline phase in both systems.

The XRD results of this study are consistent with previous work [37], which reported that aluminosilicate phases in expanded clay promote secondary pozzolanic reactions and additional formation of C-S-H gels. The reduced intensity of portlandite in the 5–10 mm mix further indicates an increase in silica consumption, in agreement with [38], where a similar behavior was observed in lightweight nanosilica-modified concretes exposed to sulphate. According to [39], the formation of crystalline phases such as quartz and feldspar improves structural stability and long-term durability in LECA-based systems. Furthermore, [40] reported that the mineral composition of expanded clay significantly influences hydration kinetics and strength development, supporting the observed relationship between phase composition and improved mechanical performance of the experimental mixture.

4.3 Microstructural Analysis

Representative SEM micrographs of lightweight concrete specimens at magnifications of $\times 2000$ and $\times 3000$ are shown in Fig. 9.

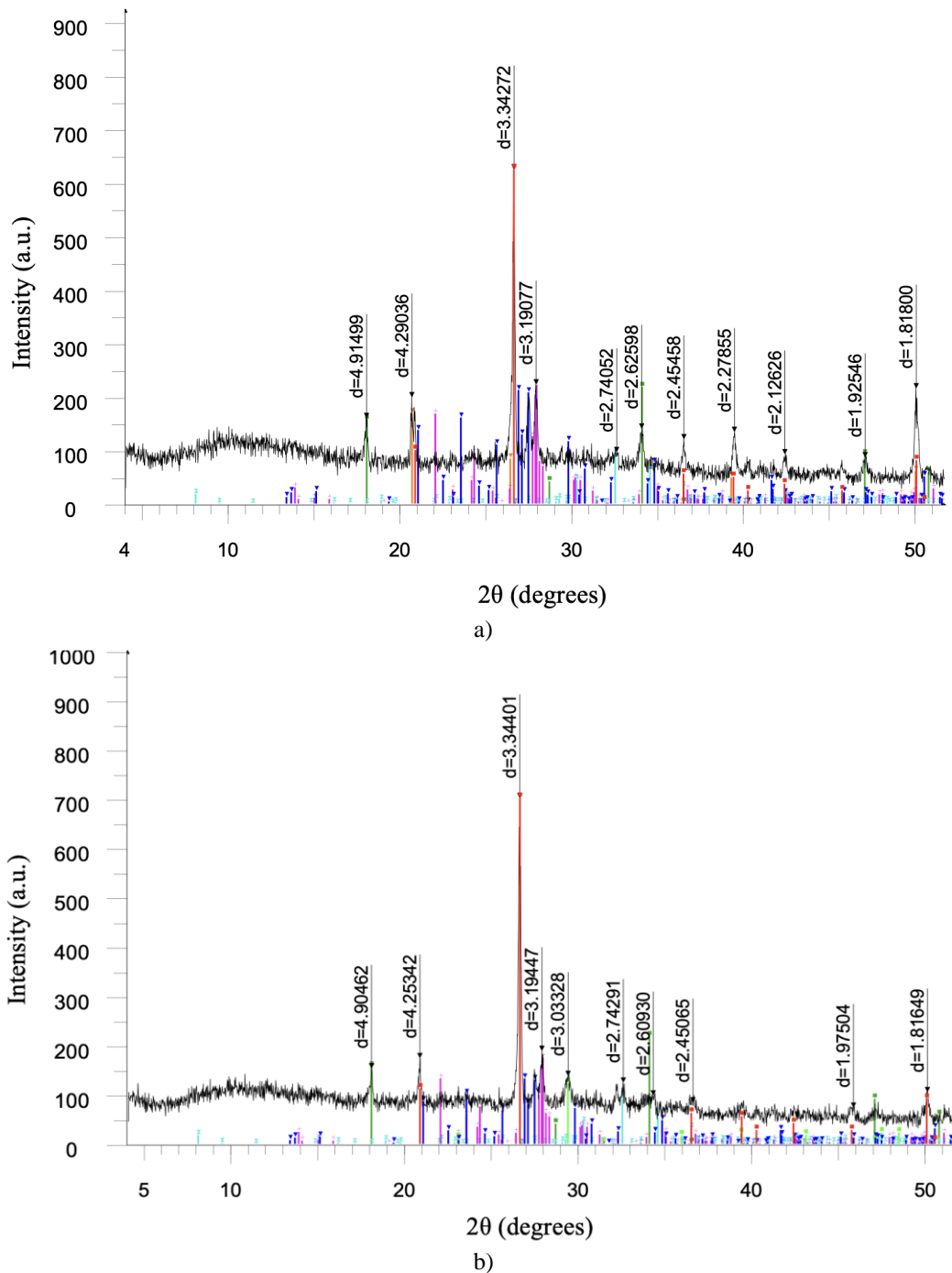


Fig. 8. XRD patterns of lightweight concrete with expanded clay aggregate fractions of 5–8 mm (a) and 5–10 mm (b).

The M1 control mix (Fig. 9) shows a heterogeneous microstructure with numerous voids and partially hydrated grains. Crystalline portlandite with hexagonal plates and fibrous C–S–H gels is evident, indicating incomplete hydration and localized densification around unreacted particles. In contrast, the experimental mix (M4) (Fig. 10) exhibits a dense, continuous matrix with well-developed C–

S–H gel and fewer pores. The interfacial transition zone (ITZ) between the aggregate and the cement paste is compact, indicating strong adhesion and minimal microcracking. The rounded features and layered gel textures visible at higher magnification correspond to secondary hydration products, consistent with the reduced portlandite content observed by XRD.

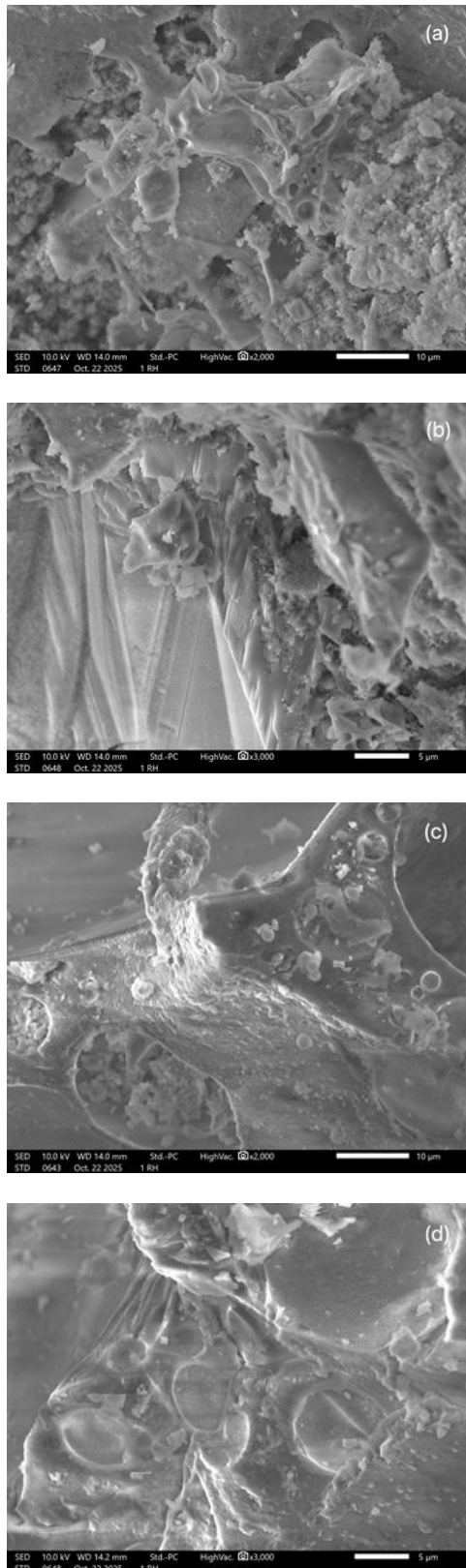


Fig. 9. SEM images of lightweight expanded clay concrete at 28 days: (a, b) control specimen M1 with porous structure; (c, d) experimental specimen M4 with dense matrix and compact ITZ

Similar mechanisms were reported in [43], showing that pre-saturation and surface roughness of lightweight aggregates enhance hydration and reduce microcracking. In addition, [37] found that the morphology of the expanded clay aggregates governs the formation of a refined interfacial transition zone, confirming the improved bond and reduced porosity observed in the experimental specimens.

Fig. 10 shows the EDS elemental maps and spectrum of lightweight expanded clay concrete (specimen M1) at 28 days. The elemental maps indicate a relatively uniform distribution of O, Si, Al, and Ca throughout the matrix. Carbon is present at low intensity, mainly associated with the cementitious matrix. Minor elements such as Mg, K, S and Fe are detected in small amounts and are evenly dispersed, reflecting the mineral composition of the expanded clay aggregate and cement. The EDS spectrum confirms the predominance of O, Si, Al, and Ca, which is typical for cement-based materials that incorporate expanded clay aggregate.

4.4 Industrial Recommendations

For the manufacture of prefabricated wall panels and volumetric blocks, it is advisable to use expanded clay aggregate with a grain size of 5–10 mm, which ensures rapid strength development and consistent technological properties. During the treatment with heat and moisture at temperatures up to 65 °C, the concrete achieves more than 60% of its target strength at stripping and up to 97% after 3 days, thereby accelerating mold turnover. To maintain workability, it is recommended to pre-wet the expanded clay and add a PCE-based superplasticizer at a dosage of approximately 1% of the cement mass, adjusted according to the aggregate's moisture content.

5. CONCLUSIONS

This study investigated new compositions of lightweight expanded clay concrete that incorporate coarse aggregates in fractions of 5–8 mm and 5–10 mm. Laboratory and production tests showed that the mixes developed with a 5–10 mm aggregate fraction achieved rapid early strength gain, stable density, and high technological quality. The experimental concrete reached more than 60% of the design strength at demolding and nearly 100% after 3 days of steam curing, while maintaining a density of 1867–1912 kg/m³—slightly lower than the control but fully compliant with lightweight concrete requirements. Full-scale tests on wall panels and volumetric blocks confirmed uniform surface quality and the absence of visible defects, indicating that the transition to experimental composition did not compromise technological or structural performance.

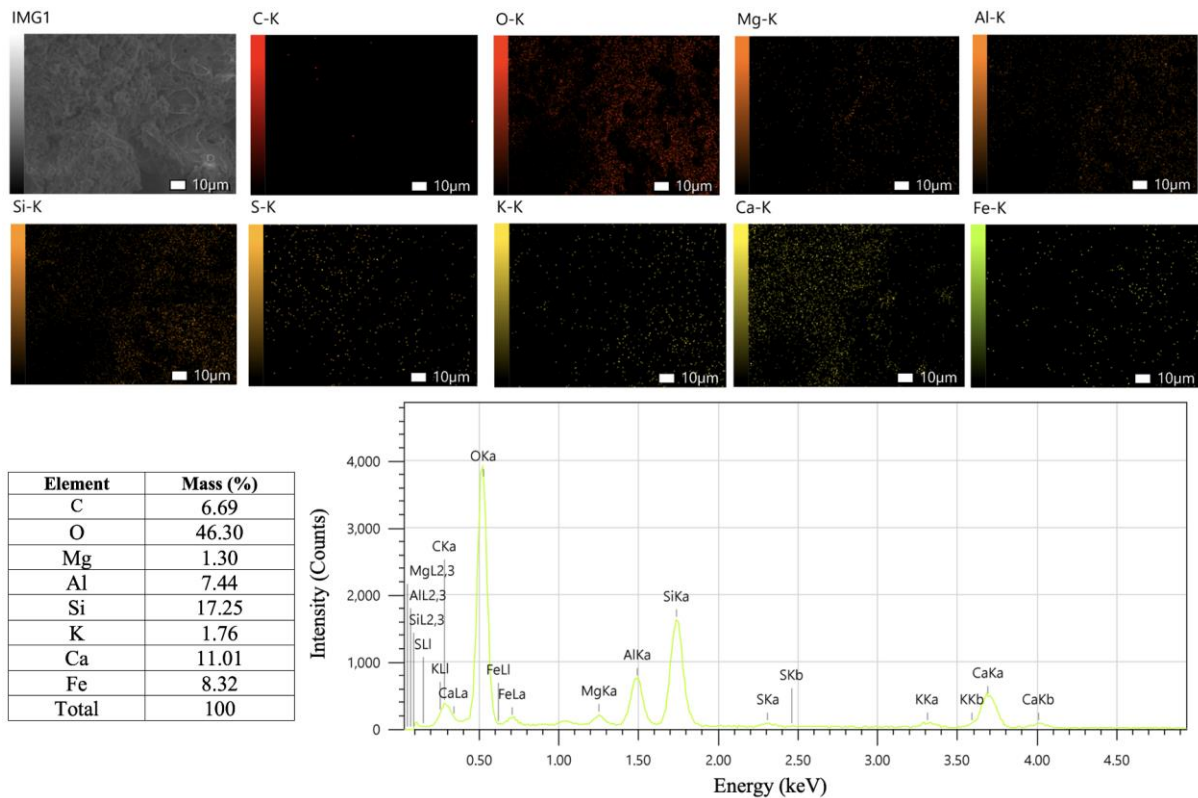


Fig. 10. EDS elemental maps and spectrum of lightweight expanded clay concrete (experimental specimen M1) at 28 days, showing the distribution of C, O, Mg, Al, Si, S, K and Ca.

The optimized particle-size distribution of the expanded clay aggregates contributed to improved strength development, reduced porosity, and enhanced microstructural compactness, as confirmed by XRD and SEM analyses. In general, the proposed lightweight expanded clay concrete mix demonstrates reliable mechanical performance and technological suitability for prefabricated and modular construction of large-scale, offering a sustainable and efficient solution for structural and insulating building elements.

Future studies should focus on the durability performance of lightweight expanded clay concrete, including water absorption, capillary suction, freeze-thaw resistance, and chloride ingress, to further validate its suitability for long-term structural applications. In addition, the effects of shrinkage and creep should be investigated, particularly in large prefabricated and modular elements. To strengthen sustainability claims, a life cycle assessment (LCA) is recommended to quantify the environmental benefits of lightweight concrete relative to conventional structural concrete.

6. REFERENCES

1. Agrawal Y., Gupta T., Sharma R., Panwar N.L., and Siddique S., A Comprehensive Review on the Performance of Structural Lightweight Aggregate Concrete for Sustainable Construction. *Construction Materials*, vol. 1, no. 1, 2021, pp. 39–62, doi: 10.3390/constrmater1010003.
2. Zhang L., Xu W., Fan D., Dong E., Liu K., Xu L., and Yu R., Understanding and Predicting Micro-Characteristics of Ultra-High Performance Concrete (UHPC) with Green Porous Lightweight Aggregates: Insights from Machine Learning Techniques. *Construction and Building Materials*, vol. 446, 2024, 138021, doi: 10.1016/j.conbuildmat.2024.138021.
3. Zhang Y., and Lu R., Effects of Recycled Lightweight Aggregates as Coarse Aggregates on Workability, Mechanical and Microstructural Behavior of Recycled Concrete. *Construction and Building Materials*, vol. 482, 2025, 141694, doi: 10.1016/j.conbuildmat.2025.141694.
4. Ismail M.K., Hassan A.A.A., AbdelAleem B.H., and El-Dakhkhni W., Flexural Behavior and Cracking of Lightweight RC Beams Containing Coarse and Fine Slag Aggregates. *Structures*, vol. 47, 2023, pp. 1005–1019, doi: 10.1016/j.istruc.2022.11.065.
5. Singh N., Raza J., Colangelo F., and Farina I., Advancements in Lightweight Artificial Aggregates: Typologies, Compositions, Applications, and Prospects for the Future. *Sustainability*, vol. 16, no. 21, 2024, 9329, doi: 10.3390/su16219329.

6. Alqahtani F.K., Abotaleb I.S., and ElMenshawey M., Life Cycle Cost Analysis of Lightweight Green Concrete Utilizing Recycled Plastic Aggregates. *Journal of Building Engineering*, vol. 40, 2021, 102670, doi: 10.1016/j.jobe.2021.102670.
7. Teshev I., Bospayev A., Zhambakina Z., Tamov M., Altigenov U., Zhussupov T., and Tolegenova A., Multi-Story Volumetric Blocks Buildings with Lower Frame Floors. *Buildings*, vol. 14, no. 6, 2024, 1655, doi: 10.3390/buildings14061655.
8. Bospaev A., Teshev I., Kuralov U.S., and Altigenov U.B., Strength and Deformations of Volume-Blocks. In *Smart Geotechnics for Smart Societies*, 1st edn, Zhussupbekov A., Sarsembayeva A., and Kaliakin V.N. (Eds.), CRC Press, 2023, pp. 85–96, doi: 10.1201/9781003299127-373.
9. Contreras M., Gázquez M.J., Romero M., and Bolívar J.P., Recycling of Industrial Wastes for Value-Added Applications in Clay-Based Ceramic Products: A Global Review (2015–19). In *New Materials in Civil Engineering*, Elsevier, 2020, pp. 155–219, doi: 10.1016/B978-0-12-818961-0.00005-3.
10. Jaha S., Carvalheiras J., Mahmoudi S., and Labrincha J., Production of Lightweight Expanded Aggregates from Smectite Clay, Palygorskite-Rich Sediment and Phosphate Sludge. *Clay Minerals*, vol. 59, no. 2, 2024, pp. 85–99, doi: 10.1180/clm.2024.10.
11. Teshev I., Bospayev A., Tamov M., Zhambakina Z., Altigenov U., Zhussupov T., and Tolegenova A., Stress State of Modular Blocks with Large Door Openings. *Buildings*, vol. 15, no. 8, 2025, 1253, doi: 10.3390/buildings15081253.
12. Farina I., Moccia I., Salzano C., Singh N., Sadrolodabae P., and Colangelo F., Compressive and Thermal Properties of Non-Structural Lightweight Concrete Containing Industrial Byproduct Aggregates. *Materials*, vol. 15, no. 11, 2022, 4029, doi: 10.3390/ma15114029.
13. Zukri A., Nazir R., Said K.N.M., and Moayedhi H., Physical and Mechanical Properties of Lightweight Expanded Clay Aggregate (LECA). *MATEC Web of Conferences*, vol. 250, 2018, 01016, doi: 10.1051/mateconf/201825001016.
14. Chi J.M., Huang R., Yang C.C., and Chang J.J., Effect of Aggregate Properties on the Strength and Stiffness of Lightweight Concrete. *Cement and Concrete Composites*, vol. 25, no. 2, 2003, pp. 197–205, doi: 10.1016/S0958-9465(02)00020-3.
15. Wei H., Liu Y., Wu T., and Liu X., Effect of Aggregate Size on Strength Characteristics of High Strength Lightweight Concrete. *Materials*, vol. 13, no. 6, 2020, 1314, doi: 10.3390/ma13061314.
16. Kennedy, C., Onyelowe, J., Jagan, J., Kontoni, D.-P. N., Moghal, A. A. B., Onuoha, I. C., Viswanathan, R., and Soni, D. K. (2023). Utilization of GEP and ANN for predicting the net-zero compressive strength of fly ash concrete toward carbon neutrality infrastructure regime. *International Journal of Low-Carbon Technologies*, 18, 902–914. <https://doi.org/10.1093/ijlct/ctad081>
17. Chung S.-Y., Sikora P., Kim D.J., El Madawy M.E., and Abd Elrahman M., Effect of Different Expanded Aggregates on Durability-Related Characteristics of Lightweight Aggregate Concrete. *Materials Characterization*, vol. 173, 2021, 110907, doi: 10.1016/j.matchar.2021.110907.
18. Abd Elrahman M., Chung S.-Y., and Stephan D., Effect of Different Expanded Aggregates on the Properties of Lightweight Concrete. *Magazine of Concrete Research*, vol. 71, no. 2, 2019, pp. 95–107, doi: 10.1680/jmacr.17.00465.
19. Chung S.-Y., Abd Elrahman M., and Stephan D., Effect of Different Gradings of Lightweight Aggregates on the Properties of Concrete. *Applied Sciences*, vol. 7, no. 6, 2017, 585, doi: 10.3390/app7060585.
20. Sim J.-I., Yang K.-H., Lee E.-T., and Yi S.-T., Effects of Aggregate and Specimen Sizes on Lightweight Concrete Fracture Energy. *Journal of Materials in Civil Engineering*, vol. 26, no. 5, 2014, pp. 845–854, doi: 10.1061/(ASCE)MT.1943-5533.0000884.
21. Ke Y., Beaucour A.L., Ortola S., Dumontet H., and Cabrillac R., Influence of Volume Fraction and Characteristics of Lightweight Aggregates on the Mechanical Properties of Concrete. *Construction and Building Materials*, vol. 23, no. 8, 2009, pp. 2821–2828, doi: 10.1016/j.conbuildmat.2009.02.038.
22. Sari D., and Pasamehmetoglu A.G., The Effects of Gradation and Admixture on the Pumice Lightweight Aggregate Concrete. *Cement and Concrete Research*, vol. 35, no. 5, 2005, pp. 936–942, doi: 10.1016/j.cemconres.2004.04.020.
23. Kursula K., Mistri A., Illikainen M., and Perumal P., Utilization of Fine Concrete Waste as a Lightweight Aggregate via Granulation: Technical and Environmental Assessment. *Journal of Cleaner Production*, vol. 434, 2024, 139938, doi: 10.1016/j.jclepro.2023.139938.
24. Thienel K.-C., Haller T., and Beuntner N., Lightweight Concrete From Basics to Innovations. *Materials*, vol. 13, no. 5, 2020, 1120, doi: 10.3390/ma13051120.
25. Aslam M., Shafiq P., Alizadeh Nomeli M., and Zamin Jumaat M., Manufacturing of High-Strength Lightweight Aggregate Concrete Using Blended Coarse Lightweight Aggregates. *Journal of Building Engineering*, vol. 13, 2017, pp. 53–62, doi: 10.1016/j.jobe.2017.07.002.

26. Ting T.Z.H., Rahman M.E., Lau H.H., and Ting M.Z.Y., Recent Development and Perspective of Lightweight Aggregates Based Self-Compacting Concrete. *Construction and Building Materials*, vol. 201, 2019, pp. 763–777, doi: 10.1016/j.conbuildmat.2018.12.128.
27. Chiadighikaobi, P.C. (2019). Effects of basalt fiber in lightweight expanded clay concrete on compressive strength and flexural strength of lightweight basalt fiber reinforced concrete. *IOP Conference Series: Materials Science and Engineering*, 640(1), 012055. <https://doi.org/10.1088/1757-899X/640/1/012055>
28. Khan, S.A., Hussain, F., Khushnood, R.A., Amjad, H., and Ahmad, F. (2024). Feasibility study of expanded clay aggregate lightweight concrete for nonstructural applications. *Advances in Civil Engineering*, 2024, 8263261. <https://doi.org/10.1155/2024/8263261>
29. Stolevich, I.A., Kostyuk, A.I., Kravchenko, S.A., and Posternak, O.O. (2021). Expanded clay concrete mixtures and concretes on carbonate sand properties improvement. *IOP Conference Series: Materials Science and Engineering*, 1164(1), 012075. <https://doi.org/10.1088/1757-899X/1164/1/012075>
30. Uysal, O., Uslu, İ., Aktaş, C.B., Chang, B., and Yaman, İ.Ö. (2024). Physical and mechanical properties of lightweight expanded clay aggregate concrete. *Buildings*, 14(6), 1871. <https://doi.org/10.3390/buildings14061871>
31. Banawair A.S., Qaid G.M., Adil Z.M., and Nasir N.A.M., The Strength of Lightweight Aggregate in Concrete – A Review. *IOP Conference Series: Earth and Environmental Science*, vol. 357, no. 1, 2019, 012017, doi: 10.1088/1755-1315/357/1/012017.
32. Mohamad H.M., Manufacture of Concrete Paver Block Using Waste Materials and By-Products: A Review. *International Journal of GEOMATE*, vol. 22, no. 93, 2022, pp. 83–90, doi: 10.21660/2022.93.j2363.
33. Mohamed S.H., Properties of Structural Lightweight High Strength Self-Compacting Concrete. *International Journal of GEOMATE*, vol. 23, no. 96, 2022, pp. 45–52, doi: 10.21660/2022.96.3292.
34. Zhagifarov, A., Awwad, T., Akhmetov, D., Suzev, N., and Kolesnikova, I. (2025). Effectiveness of road slabs produced using microsilica and fiber quality improvement. *International Journal of GEOMATE*, 28(126), 16–24. <https://doi.org/10.21660/2025.126.4335>
35. Suryanita R., Experimental Study on Performance of Cellular Lightweight Concrete Due to Exposure High Temperature. *International Journal of GEOMATE*, vol. 21, no. 83, 2021, pp. 17–24, doi: 10.21660/2021.83.6287.
36. Winarno S., Assessment of the Content of Stone Fine Powder and Raw Rice Husk in High-Performance Lightweight Rice Husk Concrete Blocks. *International Journal of GEOMATE*, vol. 25, no. 111, 2023, pp. 91–98, doi: 10.21660/2023.111.3952.
37. Bogas J.A., Mauricio A., and Pereira M.F.C., Microstructural Analysis of Iberian Expanded Clay Aggregates. *Microscopy and Microanalysis*, vol. 18, no. 5, 2012, pp. 1190–1208, doi: 10.1017/S1431927612000487.
38. Vargas P., Marín N.A., and Tobón J.I., Performance and Microstructural Analysis of Lightweight Concrete Blended with Nanosilica under Sulfate Attack. *Advances in Civil Engineering*, vol. 2018, 2715474, doi: 10.1155/2018/2715474.
39. Begentayev, M.M., Kuldeyev, E.I., Zhumadilova, Z.O., Akhmetov, D.A., Tolegenova, A.K., Zhagifarov, A.M., Nurlybayev, R.E., and Alikhan, A. (2025). Investigation of waste-based self-compacting concrete: Analysis of rheology and hydration with silica fume and fly ash. *ES Materials & Manufacturing*, 28, 1498. <https://doi.org/10.30919/mm1498>
40. Podnar T.M., and Kravanja G., Thermal, Mechanical, and Microstructural Properties of Novel Light Expanded Clay Aggregate (LECA)-Based Geopolymer Concretes. *Journal of Composites Science*, vol. 9, no. 2, 2025, 69, doi: 10.3390/jcs9020069.
41. Vijayalakshmi R., and Ramanagopal S., Structural Concrete Using Expanded Clay Aggregate: A Review. *Indian Journal of Science and Technology*, vol. 11, no. 16, 2018, pp. 1–12, doi: 10.17485/ijst/2018/v11i16/121888.
42. Becker A.R., Ozaki E.S., Lintz R.C.C., and Gachet L.A., Study of Mechanical, Acoustic, and Microstructure Properties of Lightweight Mortars Produced with Expanded Clay. *Materials Today: Proceedings*, vol. 65, 2022, pp. 1222–1229, doi: 10.1016/j.matpr.2022.04.181.
43. Özkılıç Y.O., Beskopylny A.N., Stel'makh S.A., et al., Lightweight Expanded-Clay Fiber Concrete with Improved Characteristics Reinforced with Short Natural Fibers. *Case Studies in Construction Materials*, vol. 19, 2023, e02367, doi: 10.1016/j.cscm.2023.e02367.
44. Yew M.K., Yew M.C., Beh J.H., et al., Effect of Pre-Soaking Treatment Method of Plant-Based Aggregate on the Properties of Lightweight Concrete—Preliminary Study. *Coatings*, vol. 13, no. 5, 2023, 864, doi: 10.3390/coatings13050864.
45. Bu, Changming, Haiyan Yang, Lei Liu, Dongxu Zhu, Yi Sun, Linwen Yu, Yuhui Ouyang, Xuemei Cao, and Qike Wei. 2022. “Quantification of Ceramsite Granules in Lightweight Concrete Panels through an Image Analysis Technique.” *Materials* 15(3):1063. doi:10.3390/ma15031063.

46. Chiadighikaobi, P. C. 2019. "Effects of Basalt Fiber in Lightweight Expanded Clay Concrete on Compressive Strength and Flexural Strength of Lightweight Basalt Fiber Reinforced Concrete." *IOP Conference Series: Materials Science and Engineering* 640(1):012055. doi:10.1088/1757-899X/640/1/012055.
47. Ding, Weihua, Lin Zhu, Hu Li, Bin Hou, and Fan Yang. 2022. "Mechanical and Thermal Properties of Shale Ceramsite Concrete: Experimental Study on the Influence Law Due to Microencapsulated Phase-Change Material Content and Phase-Change Cycle Numbers" edited by J. Han. *Advances in Civil Engineering* 2022(1):2720956. doi:10.1155/2022/2720956.
48. Khan, Shayan Ali, Fazal Hussain, Rao Arsalan Khushnood, Hassan Amjad, and Farhan Ahmad. 2024. "Feasibility Study of Expanded Clay Aggregate Lightweight Concrete for Nonstructural Applications" edited by A. Babafemi. *Advances in Civil Engineering* 2024(1):8263261. doi:10.1155/2024/8263261.
49. Li, Min, Yongjun Wang, Jiaolong Ren, Hongbo Zhao, Shenghan Zhuang, and Jian Wang. 2024. "Evaluation and Prediction of Fatigue Life for Ceramsite Lightweight Concrete Considering the Effects of Ceramsite Aggregate Size and Content." *Case Studies in Construction Materials* 21:e03613. doi:10.1016/j.cscm.2024.e03613.
50. Li, Yijing, Yuan Yang, Shuaicheng Guo, Md Zillur Rahman, and Deju Zhu. 2026. "A Comprehensive Review of Ceramsite Concrete: Design, Performance and Sustainable Applications." *Journal of Building Engineering* 117:114709. doi:10.1016/j.job.2025.114709.
51. Li, Zhe, Mengmeng Li, Heng Yang, and Jiangying Chen. 2025. "Experimental Study and Numerical Simulation of the Dynamic Mechanical Properties of Ceramsite Concrete Containing Different Types of Coarse Aggregates." *Case Studies in Construction Materials* 22:e04431. doi:10.1016/j.cscm.2025.e04431.
52. Uysal, Orkun, İlbüke Uslu, Can B. Aktaş, Byungik Chang, and İsmail Özgür Yaman. 2024. "Physical and Mechanical Properties of Lightweight Expanded Clay Aggregate Concrete." *Buildings* 14(6):1871. doi:10.3390/buildings14061871.
53. Yang, Kangqing, Shenghan Zhuang, Yongjun Wang, Jiashu Li, Shuo Zhou, and Jiaolong Ren. 2025. "Crack Propagation of Ceramsite Lightweight Concrete Under Four-Point Bending Fatigue Conditions." *Materials* 18(13):2957. doi:10.3390/ma18132957.

Copyright © Int. J. of GEOMATE All rights reserved, including making copies, unless permission is obtained from the copyright proprietors.
