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RESEARCH PAPER

Comparative Analysis of Perlite and Leca in Lightweight Concrete for Non-structural Applications

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Abstract

This study investigates lightweight concrete incorporating perlite and lightweight expanded clay aggregate (LECA) for non-structural applications. Four mixture designs (Types I–IV) are developed to systematically evaluate the impact of replacing conventional aggregates on mechanical performance, durability, density, and thermal conductivity. Increasing perlite and LECA content led to significant reductions in specific gravity (from 2.47 to 0.90 g/cm^3), compressive strength (from 31.59 to 6.35 MPa), and thermal conductivity (from 1.45 W/m·K to 0.32 W/m·K), values that align well with practical requirements for non-structural elements: partition walls typically require 5–15 MPa compressive strength and moderate durability, insulation panels demand thermal conductivity below 0.5 W/m·K (with "excellent" performance < 0.35 W/m·K), and lightweight fill systems prioritize density under 1.0 g/cm^3 to reduce dead load. Strong linear correlations (R^2 up to 0.9996) between aggregate replacement levels and concrete properties enable precise mix design tailored to specific application criteria. However, increased water absorption (up to 15.5%) and reduced freeze–thaw resistance (a relative dynamic modulus drop from 92 to 70%) highlight durability limitations in harsh environments, necessitating protective measures or supplementary materials in moisture-prone or cold climates. The study's novelty lies in its comprehensive comparative framework across four substitution levels, providing engineers with regression-based tools to optimize perlite–LECA concrete for energy-efficient, sustainable construction while balancing performance and serviceability requirements.

Keywords Lightweight concrete · Perlite aggregate · LECA · Thermal insulation · Compressive strength · Non-structural applications

Abbreviations

LWC	Lightweight concrete
LWA	Lightweight aggregates
LECA	Lightweight expanded clay aggregate
RDM	Relative dynamic modulus
ITZ	Interfacial transition zone
PCE	Polycarboxylate ether
W/C	Water-to-cement ratio
SSD	Saturated surface-dry
ANOVA	Analysis of variance
MSW	Municipal solid waste
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
SE	Sand equivalent
ISIRI	Institute of Standards and Industrial Research of Iran

1 Introduction

Lightweight concrete has become an indispensable material in modern construction, particularly for non-structural applications where thermal performance, acoustic insulation, and weight reduction are prioritized over high mechanical loading. This class of concrete relies fundamentally on lightweight aggregates (LWAs), with expanded perlite and lightweight expanded clay aggregate (LECA) standing out as two of the most technically and commercially relevant

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options. Defined by international standards such as EN 13055 (2016) and ASTM C330 (2023), these aggregates can be either naturally occurring—as in the case of perlite, a low-calcium aluminosilicate of volcanic origin—or industrially manufactured, like LECA, which is produced by firing clay at 1050–1250 °C to induce controlled expansion, yielding a porous, lightweight structure with enhanced resistance to alkaline corrosion and frost action (Podnar and Kravanja 2025; Kozhukhova et al. 2024).

The selection between perlite and LECA is rarely arbitrary; it reflects a deliberate engineering trade-off between functional performance and structural adequacy. Perlite, due to its highly porous and amorphous structure, delivers exceptional thermal insulation—with studies indicating up to 18% better performance than LECA at comparable densities, and thermal conductivity values as low as 0.07 W/m·K (Drozdzol 2021). This makes it ideal for applications such as non-load-bearing exterior walls and chimney systems, where energy efficiency and fire safety are paramount. In chimney construction, for instance, perlite concrete enables heat recovery efficiencies of at least 23%—far exceeding the 5.5% achieved by LECA-based alternatives—while eliminating the need for mineral wool insulation through the strategic use of air layers (Drozdzol 2021). Its low density also translates into tangible economic benefits: reduced transportation costs, easier on-site handling, and lower labor requirements during installation and finishing. Moreover, perlite concrete blocks are more amenable to machining, allowing for cleaner cuts and aesthetically superior surface finishes (Drozdzol 2021).

LECA, by contrast, offers a more balanced profile—particularly in mechanical performance. While its thermal conductivity is higher than perlite's, it compensates with superior compressive and tensile strength characteristics, especially when used as a partial sand replacement in geopolymer systems, where compressive strength gains of up to 44% at 3 days and 27% at 28 days have been recorded (Youssf et al. 2022). Even when used as a full coarse aggregate replacement—which typically reduces compressive strength by up to 38%—LECA-based concrete maintains a higher strength-to-weight ratio than conventional concrete, making it uniquely suited for thermally sensitive, low-load applications such as insulation panels and partition walls (Podnar and Kravanja 2025; Baziak et al. 2021; Rajalekshmi and Jose 2023). Its bulk density in concrete form typically ranges between 1042 and 1200 kg/m^3, with up to 28% reduction in overall concrete density compared to normal-weight mixes (Drozdzol 2021; Rajalekshmi and Jose 2023). The closed-pore structure of LECA contributes to this density reduction, but can lead to lower crushing strength if particle fragmentation occurs during mixing or placement (Rajalekshmi and Jose 2023).

Beyond thermal and mechanical properties, durability and transport-related performance further differentiate these materials. Water permeability tests reveal that LECA exhibits the highest permeability among common lightweight aggregates—followed by scoria, with perlite performing best in limiting water ingress (Dolatabad et al. 2020). However, in terms of water absorption capacity, perlite leads—absorbing more water than LECA, which in turn absorbs more than conventional aggregates (Dolatabad et al. 2020). This inherent porosity, while beneficial for insulation, introduces challenges in long-term durability, particularly under conditions of thermal cycling or moisture variation, where internal stresses can compromise structural integrity (Rajalekshmi and Jose 2023). Workability is another critical factor: complete sand replacement with LECA can reduce concrete slump by 14% due to its angularity and water demand, whereas perlite's finer texture and lower density facilitate easier placement and finishing (Drozdzol 2021; Youssf et al. 2022).

These material-specific advantages are not merely academic—they translate directly into real-world engineering decisions across diverse sectors. In fire-prone infrastructure such as skyscrapers and nuclear facilities, geopolymer-based ultra-high-performance concrete (G-UHPC) incorporating silica fume and quartz powder achieves compressive strengths up to 156 MPa at ambient conditions and retains 24–28% of that strength at 800 °C—demonstrating the critical role of material selection in extreme environments (Elhefny et al. 2025). In marine tidal zones, predictive chloride ingress models based on ACI 138 and JSCE Guide standards govern the design of port and dock structures, where water-cement ratios and exposure duration dictate long-term corrosion resistance (Abdellatief et al. 2025). For impact-resistant applications—such as blast walls and highway barriers—preplaced aggregate geopolymer concrete reinforced with steel mesh and 5D fibers delivers compressive strengths of 37–56 MPa alongside enhanced ductility, meeting stringent defense and transportation safety codes (Samadi et al. 2025). These examples underscore that lightweight concrete is not a compromise—it is a precision-engineered solution, where the choice of aggregate must align with environmental exposure, structural demand, and lifecycle performance goals.

Yet, despite the well-documented individual profiles of perlite and LECA, and despite the urgent global imperative to decarbonize construction—an industry responsible for 8% of global CO_2 emissions and burdened by 20–25% transport energy costs due to concrete's high density (~2.5 g/cm^3)—a critical research gap persists: there is no systematic, integrated study evaluating the combined use of perlite and LECA in concrete systems.

Table 1 Results of the cement soundness test

Sample no.	1	2	3	4
Length expansion (%)	0.06	0.09	0.11	0.08

Table 2 Summary of key properties of raw materials

Material	Key parameter	Value	Reference standard
Ardabil cement	Density (kg/m^3)	3130	(ASTM C618–25a 2025)
	Autoclave expansion (%)	<0.8	(ASTM C151, C151M-23 2023)
River gravel	Density (kg/m^3)	2650	(ASTM C33/C33M-18 2023)
	Water absorption (%)	1.6	(ASTM C33/C33M-18 2023)
River sand	Density (kg/m^3)	2600	(ASTM C33/C33M-18 2023)
	Water absorption (%)	2.1	(ASTM C33/C33M-18 2023)
	Fineness modulus	2.84	(ASTM C33/C33M-18 2023)
Perlite	Density (kg/m^3)	873	(ASTM C330–05 2023)
	Water absorption (%)	25	(ASTM C330–05 2023)
	Particle size range (mm)	0–2.5	(ASTM C330–05 2023)
Leca	Density (kg/m^3)	550	(ASTM C330–05 2023)
	Water Absorption (%)	19	(ASTM C330–05 2023)
	Particle Size Range (mm)	4–10	(ASTM C330–05 2023)

All comprehensive raw data regarding physical, chemical, and particle size distribution properties of raw materials (Table 34, 35, 36, 37, 38, 39, 40, 41 and Figs. 36 and 37) are provided in Appendix A

Current literature treats these materials as mutually exclusive alternatives. Studies focus on perlite or LECA—examining their effects on density, strength, permeability, or thermal conductivity in isolation. This siloed approach leaves designers without guidance on how these aggregates might interact synergistically—or antagonistically—when blended. Can the thermal superiority of perlite be combined with the mechanical robustness of LECA to create a composite LWA system that outperforms either material alone? How do volumetric substitution ratios affect workability, curing behavior, or long-term durability? What is the optimal balance to achieve target compressive strengths (e.g., 15 MPa for non-structural elements (Ragab et al. 2023)) while maximizing insulation and minimizing environmental footprint?

The absence of answers to these questions forces practitioners into binary trade-offs—choosing insulation over strength, or durability over workability—when a blended solution might offer a superior, balanced performance. This lack of holistic understanding is a primary barrier to wider adoption of lightweight concrete, especially in applications where its benefits are most pronounced: non-structural elements, where 25–30% density reduction can translate into 20–25% lower transport costs and 10–12% reductions in embodied CO_2.

This study directly addresses that gap. We present the first comprehensive experimental investigation of combined perlite (0–32.9% by volume) and LECA (0–44% by volume) substitutions across four distinct concrete mix designs. We evaluate not only individual effects but—crucially—their synergistic interactions on mechanical performance (compressive, tensile, and flexural strength), physical properties (density, thermal conductivity, water absorption), and durability indicators (permeability, resistance to environmental cycling). The goal is not merely to add to the literature, but to provide engineers and material scientists with an evidence-based framework for optimizing lightweight concrete formulations—enabling the design of sustainable, high-performance building components tailored to specific environmental, structural, and economic constraints.

By bridging this critical knowledge gap, this research aims to accelerate the transition toward lighter, greener, and more intelligent concrete systems—unlocking the full potential of lightweight aggregates in the pursuit of sustainable urban development.

2 Materials and Methods

2.1 Materials

This This study utilized pozzolanic Portland cement from Ardabil Cement Factory (density: 3130 kg/m^3), verified for stability through a soundness test per (ASTM C151/C151M-23 2023). Prismatic specimens (1 × 1 inch cross-section, 12 inches long) were cured for 24 h, autoclaved at 2 MPa steam pressure and 216 °C for 3 h, yielding expansions of 0.06%, 0.09%, 0.11% and 0.08% (Table 1), all below the 0.8% limit, confirming suitability. The key physical and chemical properties of all raw materials—including cement, gravel, sand, perlite, and Leca—are summarized in Table 2. All comprehensive raw data (including detailed chemical compositions, particle size distributions, and precise physical properties) are provided in Appendix A.

Crushed gravel and rounded sand from the Sefid-rud River were used, with densities of 2650 kg/m^3 and 2600 kg/m^3 and water absorptions of 1.6% and 2.1% respectively. Gravel had a maximum nominal size of 19 mm, and sand had a fineness modulus of 2.84 (within 2.3–3.1), both compliant with (ASTM C33/C33M-18 2023). Sand quality was confirmed via the sand equivalent test per (ASTM D2419-22 2022). Perlite from Gostaresh Perlite Azerbaijan factory was used in three grades (R1: 0–0.15 mm, 20%; R3: 0.5–1.0 mm, 20%; R4: 1.0–2.5 mm, 60%), with 25% water absorption and a density of 873 kg/m^3. Structural Leca from

Iran Leca Factory had a density of 550 kg/m^3, 19% water absorption, and a particle size range of 4–10 mm. Potable water from Parsabad County, complying with (ASTM C1602/C1602M-22 2022), was used for mixing.

2.2 Mix Design Rationale

The four mix designs (Types I–IV) were developed to systematically investigate the effects of replacing conventional aggregates with lightweight aggregates (perlite and LECA) at varying levels, ranging from low to high substitution, to comprehensively capture their impact on mechanical properties, durability, and thermal performance. The specific replacement levels, such as 32.9% perlite and up to 44% LECA in Type IV, were selected based on a combination of preliminary experimental results, industry practices, and literature recommendations. These levels were chosen to balance lightweight properties (e.g., reduced density and improved thermal insulation) with adequate mechanical performance for non-structural applications, such as interior partition walls, thermal insulation panels, and lightweight fill systems.

Preliminary experiments indicated that replacement levels between 20 and 50% for lightweight aggregates provide an optimal trade-off between density reduction and strength retention, aligning with industry standards such as (ASTM C330-05 2023), which specifies requirements for lightweight aggregates in concrete. For instance, the 32.9% perlite replacement in Type IV was selected to achieve a target density below 1.0 g/cm^3, suitable for insulation-focused applications, while maintaining a compressive strength above 5 MPa, as required for partition walls and lightweight fills. Similarly, LECA replacement levels up to 44% were chosen to enhance workability and further reduce density while ensuring compliance with typical mix proportions for non-structural concrete, as supported by studies such as (Elhefny et al. 2025 and Samadi et al. 2025). These studies recommend aggregate replacement levels of 20–50% to achieve density ranges of 0.9–1.8 g/cm^3 and thermal conductivity values of 0.3–0.5 W/m·K, which are ideal for energy-efficient building components.

The four mix designs were structured as follows:

Type I: Low replacement (e.g., 10% perlite, 0% LECA) to serve as a baseline with minimal lightweight aggregate content, representing conventional lightweight concrete mixes.

Type II: Moderate replacement (e.g., 20% perlite, 10% LECA) to evaluate intermediate effects on density and strength, aligning with common industry proportions for partition walls.

Type III: Higher replacement (e.g., 25% perlite, 20% LECA) to assess the impact of increased lightweight aggregate content, suitable for insulation panels.

Type IV: Maximum replacement (e.g., 32.9% perlite, 44% LECA) to push the boundaries of lightweight properties, targeting applications like lightweight fill systems with minimal strength requirements.

These replacement levels were carefully calibrated to cover a spectrum of practical applications while ensuring compatibility with standard mix design practices. The detailed compositions of the mix designs are presented in Table 3, which outlines the exact percentages of perlite and LECA, along with their correspondence to target applications and industry standards.

2.3 Mix Preparation and Workability Management

To ensure consistency in comparing the properties of lightweight concrete mixes, all mix designs (Types I to IV) were designed to achieve a constant slump of 2.5 cm, in accordance with (ASTM C143, C143M-20 2020). However, achieving this slump was challenging, particularly in mixes with high perlite (up to 32.9%) and LECA (up to 44%) contents, due to the high water absorption of these aggregates (25% for perlite and 19% for LECA). This high absorption led to reduced workability, especially in Type III and IV mixes, where the proportion of lightweight aggregates was maximized. To address these challenges, the following adjustments were implemented:

1. **Use of superplasticizer:** A polycarboxylate ether (PCE) superplasticizer was used at dosages ranging from 0.5% to 1.2% by cement weight to maintain the target slump of 2.5 cm. The exact dosage for each mix

Table 3 Mix design compositions and target applications

Mix design	Perlite (%)	LECA (%)	Conventional aggregate (%)	Target density (g/cm^3)	Target compressive strength (MPa)	Target thermal conductivity (W/m·K)	Target application
Type I	10	0	90	1.8–2.0	15–20	0.5–0.7	Partition walls
Type II	20	10	70	1.5–1.8	10–15	0.4–0.6	Partition walls, insulation panels
Type III	25	20	55	1.2–1.5	8–12	0.3–0.5	Insulation panels
Type IV	32.9	44	23.1	0.9–1.0	5–10	0.3–0.4	Lightweight fill systems

was determined through preliminary trials to ensure the desired workability without causing segregation or bleeding.

2. **Pre-soaking of aggregates:** To reduce water absorption during mixing, perlite and LECA aggregates were pre-soaked to a saturated surface-dry (SSD) condition. This involved soaking the aggregates in water for 24 h and then surface-drying them to prevent the addition of excess water to the mix.
3. **Adjusted mixing sequence:** The mixing sequence was modified to first blend the lightweight aggregates (perlite and LECA) with 50% of the mixing water for 1 min to allow initial water absorption. Subsequently, the cement, conventional aggregates (gravel and sand), and remaining water were gradually added and mixed for an additional 3 min to prevent stickiness and clumping.

These adjustments ensured a consistent 2.5 cm slump across all mixes while maintaining mix uniformity and quality. Table 4 summarizes the details of these adjustments and the associated mixing challenges for each mix type.

2.4 Quality Control of Materials and Mixing Process

To ensure consistency and minimize variability in the properties of lightweight concrete mixes, rigorous quality control measures were implemented in the selection and preparation of materials and the mixing process. The grading of perlite (Appendix A, Table 37) and LECA (Appendix A, Table 40) aggregates was precisely controlled to ensure a consistent particle size distribution. Perlite was used in four grades (R_1: 0–0.15 mm, 20%; R_3: 0.5–1.0 mm, 20%; R_4: 1.0–2.5 mm, 60%), and LECA had a particle size range of 4–10 mm, both compliant with (ASTM C330-05 2023). These consistent gradings were verified through meticulous sieving and preliminary testing to prevent variations in mix properties. Additionally, the mixing process was conducted using a constant-speed mixer (150 rpm) with a modified mixing sequence. As described in the “Mix Preparation and Workability Management” section, lightweight aggregates (perlite and LECA) were first blended with 50% of the mixing water to allow initial water absorption, followed by the gradual addition of cement, conventional aggregates, and the remaining water. This sequence helped reduce stickiness and segregation. A polycarboxylate ether (PCE) superplasticizer was used at dosages ranging from 0.5% to 1.2% by cement weight (Table 3) to maintain a consistent slump of 2.5 cm, contributing to uniform mix workability. These quality control measures minimized variability in mix properties and ensured batch consistency.

2.5 Experimental Program and Testing Methodology

The experimental investigation was conducted on 32 mix designs of lightweight concrete, with a total of 204 cubic specimens (150 × 150 × 150 mm) prepared and tested in accordance with ASTM standards to ensure reliability and reproducibility. Concrete mixing was performed using a horizontal drum mixer (60–160 RPM) as specified in (ASTM C94/C94M-23 2024), with materials introduced in the sequence of lightweight aggregates (Leca and perlite), natural aggregates, water, and finally cement, to account for the high water absorption of Leca (~19%) and perlite (~25%). Mixing continued for 3–8 min after cement addition to ensure homogeneity. Specimens were cast in steel molds coated with a release agent per ASTM C192 (ASTM C192/C192M-19 2024), with concrete placed in three equal layers, each compacted by 30 strokes of a 1.8 kg tamping rod. After 24 h of curing in a high-humidity environment (≥95% RH), specimens were demolded and transferred to a water tank maintained at 22 ± 2 °C for 28 days (± 8 h) in compliance with ASTM C511 (ASTM C511–21 2021). Compressive strength was determined at 28 days using a 2000 kN universal testing machine at a loading rate of 0.25 ± 0.05 MPa/s, following ASTM C39 (ASTM C39/C39M-21 2021), while workability was monitored via slump tests per ASTM C143 (ASTM C143/C143M-20 2020). Dimensional accuracy and mass were verified using a caliper (0.1 mm precision) and digital scale (0.1 g precision), respectively. Notably, failure patterns in lightweight mixes revealed crack propagation through the porous Leca and perlite particles, contrasting with conventional concrete, where cracks typically initiate at the aggregate-paste interface, indicating a shift in failure mechanism due to the intrinsic weakness of the lightweight aggregates.

Table 4 Adjustments for achieving consistent slump and managing mixing challenges

Mix type	Perlite replacement (%)	LECA replacement (%)	PCE dosage (% by cement weight)	Pre-soaking status	Mixing sequence	Mixing challenges
Type I	0	0	0.5	Not required	Standard	None
Type II	15	15	0.7	SSD	Modified	Slight workability reduction
Type III	32.9	15	1.0	SSD	Modified	Workability reduction, stickiness
Type IV	32.9	44	1.2	SSD	Modified	Severe workability reduction, stickiness

Table 5 Mix proportions for concrete Types I–IV

Component (kg/m^3)	Type I	Type II	Type III	Type IV
Cement	350	350	350	350
Water	210	200	190	168
Sand	800	600	400	200
Gravel	1000	750	500	250
Perlite	0	69.6	139.2	208.8
Leca	0	110	220	330
Water-to-cement ratio	0.60	0.57	0.54	0.48
Perlite replacement (% of sand)	0%	11.6%	23.2%	32.9%
Leca replacement (% of gravel)	0%	11%	22%	44%

The mix design strategy, summarized in Table 5, included four distinct types (I–IV) that systematically replaced natural sand with perlite (up to 32.9%) and gravel with Leca (up to 44%), while maintaining a constant cement content of 350 kg/m^3 across all mixes. Water content was adjusted between 168 and 210 kg/m^3 to achieve a target slump of 2.5 cm, resulting in water-to-cement (W/C) ratios ranging from 0.48 to 0.60. The use of lightweight aggregates—perlite (~0.15 g/cm^3) and Leca (~0.5 g/cm^3)—enabled a 25–30% reduction in concrete density compared to conventional mixes (~2.65 g/cm^3 for sand and gravel), contributing to lower transportation energy (20–25%) and reduced CO_2 emissions (10–12%) during production, in alignment with sustainable construction goals (Rajalekshmi and Jose 2023; Khoshvatan and Pauraminia 2021). The control mix (no perlite or Leca) served as a baseline, followed by incremental substitutions to evaluate the trade-off between weight reduction and mechanical performance. A total of 192 specimens were tested for the 32 primary mix designs (six per mix), with an additional 12 specimens tested for the control mix to ensure statistical robustness. Analysis of variance (ANOVA) was applied to assess the significance of strength variations at a 95% confidence level, confirming the reliability of the observed trends.

The results indicate that while Type II and Type IV mixes achieved significant density reductions (e.g., 1.68 g/cm^3 in Type II, Appendix A, Table 52) and acceptable workability, compressive strength decreased with increasing perlite content, reaching a minimum of~6.6 MPa in high-perlite mixes, which limits their use to non-structural applications. The high porosity of perlite and Leca, while beneficial for weight reduction, compromises durability under freeze–thaw or sulfate exposure conditions (Dolatabad et al. 2020). To mitigate these limitations, the study suggests incorporating supplementary cementitious materials or nanoscale additives (e.g., nanosilica) to enhance strength by 20–30% (Chellapandian et al. 2023), optimizing mixing procedures for uniform aggregate dispersion, and employing advanced curing techniques to minimize strength variability. Table 5 provides a clear framework for scalable mix design, enabling engineers to tailor concrete properties based on application requirements—ranging from structural elements (Type I) to ultra-lightweight non-load-bearing systems (Type IV). This systematic approach supports the development of sustainable, high-performance lightweight concrete with predictable behavior and controlled property gradients.

3 Results and Discussion

3.1 Mechanical Properties

Mix Design Type I investigates the progressive replacement of natural sand with perlite in conventional gravel-based concrete, aiming to evaluate the trade-off between lightweight characteristics and mechanical performance. As outlined in Table 6, nine mix designs were formulated in accordance with (ACI 211.2-98 2004), maintaining constant gravel (42.5%) and cement (9.3%) content while perlite content increased from 0 to 32.9% at the expense of sand, which decreased from 30.2 to 0%. The water-to-cement (W/C) ratio was systematically reduced from 0.57 to 0.48 to maintain workability, which was consistently achieved at a 2.5 cm slump across all mixes, as confirmed by the test results in Appendix A (Tables 42, 43, 44, 45, 46, 47, 48, 49, 50). The average results, summarized in Table x7, demonstrate a significant reduction in specific gravity from 2.47 g/cm^3 (Mix 1) to 1.61 g/cm^3 (Mix 9)—a 34.8% decrease—driven by the substitution of dense sand (~2.65 g/cm^3) with highly porous perlite (~0.15 g/cm^3). Concurrently, 28-day compressive strength declined sharply from 31.71 MPa to

Table 6 Volumetric proportions of mix design Type I (% by volume)

Mix no.	Gravel (%)	Cement (%)	Water (%)	Sand (%)	Perlite (%)	W/C ratio
1	42.5	9.3	18.0	32.9	0.0	0.57
2	42.5	9.3	17.5	26.6	3.8	0.56
3	42.5	9.3	17.3	22.8	6.7	0.55
4	42.5	9.3	17.0	19.0	11.4	0.54
5	42.5	9.3	16.8	15.2	15.2	0.53
6	42.5	9.3	15.9	11.4	19.0	0.51
7	42.5	9.3	15.7	7.6	22.8	0.50
8	42.5	9.3	15.7	3.8	26.6	0.49
9	42.5	9.3	15.3	0.0	32.9	0.48

Table 7 Average results from nine experimental stages for mixture design Type I

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	30.2	9.3	–	18	0.57	2.5	2.47	31.71
2	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	22.39
3	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	18.65
4	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	14.76
5	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.62
6	42.5	13.3	9.3	19	15.9	0.51	2.5	1.86	9.15
7	42.5	9.8	9.3	22.8	15.7	0.50	2.5	1.81	7.58
8	42.5	6.1	9.3	26.6	15.7	0.49	2.5	1.76	6.96
9	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.35

6.35 MPa, representing a 79.9% reduction due to perlite's low particle strength, weak interfacial bonding with the cement matrix, and disruption of mechanical interlocking within the microstructure. The strength degradation is particularly pronounced in the initial stages of perlite addition (up to 15%), where each 1% increase in perlite results in an average strength loss of approximately 0.9 MPa (Table 7). Beyond 20% replacement, the rate of decline slows, suggesting a threshold beyond which the matrix becomes dominated by perlite's properties and further additions have a diminishing effect on strength. The consistent slump values across all mixes indicate that workability can be effectively controlled through incremental water reduction, despite perlite's low water absorption compared to other lightweight aggregates. The standard deviation of compressive strength decreases from 1.63 MPa (Mix 1) to 0.28 MPa (Mix 9), as derived from the data in Appendix A (Tables 42 and 50), indicating improved batch consistency at higher perlite contents due to the uniform particle size and distribution of perlite, enhancing mix homogeneity. This observation aligns with findings by (Dolatabad et al. 2020, Khoshvatan and Pauraminia 2021), who reported that porous lightweight aggregates can improve mixing uniformity despite their mechanical limitations. When compared to Mix Design Type II (LECA-based), Type I exhibits higher initial strength but less density reduction (1.61 vs. 0.90 g/cm^3 at maximum perlite), highlighting the synergistic effect of combining two lightweight aggregates. However, Type I is better suited for applications requiring moderate strength with reduced weight, such as structural walls or floor systems, whereas Type II is more appropriate for non-load-bearing, ultra-lightweight applications. The results confirm that perlite is highly effective in reducing concrete density and improving mix uniformity, but its use beyond 20% significantly compromises structural integrity. This design provides a reliable framework for tailoring concrete properties in sustainable construction, particularly where a balance between weight reduction and mechanical performance is required.

A comprehensive linear regression analysis was conducted using experimental data from Mix Design Type I (Table 7) to evaluate the impact of perlite content on key concrete properties, with results visualized in Figs. 1, 2, 3, 4, 5, 6, 7. The analysis reveals strong, predictable trends, confirming that perlite substitution significantly influences the physical and mechanical behavior of concrete.

As shown in Fig. 1, a strong negative correlation exists between perlite content and water demand, described by the equation ($y=-0.0849x+17.8833$), with an (R^2) of 0.9414. This indicates that 94.14% of the variability in water content is explained by perlite addition. Each 1% increase in perlite reduces water demand by approximately 0.0849%, attributed to perlite's porous structure (~0.15 g/cm^3) and internal water absorption, which lowers the free water needed for workability.

This effect is mirrored in the water-to-cement (W/C) ratio, which decreases from 0.57 to 0.48 as perlite content increases from 0% to 32.9% (Fig. 2, $y=-0.0029x+0.5708$, $R^2=0.9861$). The high (R^2) value (98.61%) underscores the strong correlation and reliability of W/C as a controlled parameter in lightweight mix design.

Replacing dense sand (~2.65 g/cm^3) with lightweight perlite significantly reduces specific gravity, dropping from 2.47 g/cm^3 to 1.61 g/cm^3 (Fig. 3, $y=-0.0246x+2.3703$, $R^2=0.9582$). The steep slope highlights perlite's dominant role in density reduction. This trend is further supported by a positive correlation between W/C ratio and specific gravity (Fig. 5, $y=8.2703x—2.3565$, $R^2=0.9414$), where a higher W/C ratio corresponds to lower perlite content and thus higher density.

A critical trade-off is observed in compressive strength, which decreases from 31.71 MPa to 17.73 MPa as perlite content increases to 32.9% (Fig. 4, $y=-7.3883x+260.7063$, $R^2=0.8526$). This decline reflects perlite's weak interfacial bonding and low load-bearing capacity. Although the R^2 is lower than other regressions, the model effectively captures the mechanical degradation due to perlite incorporation.

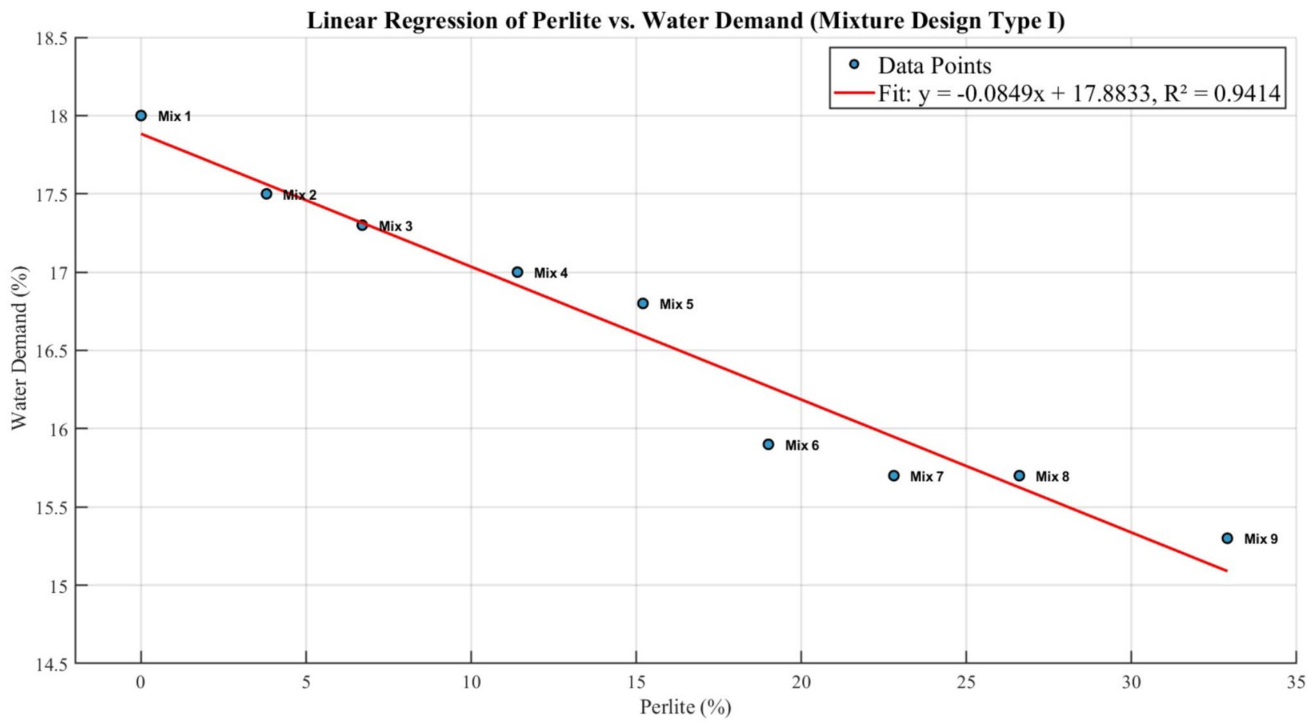

Fig. 1 Linear regression plot of perlite (%) vs. water demand (%) for mixture design Type 1

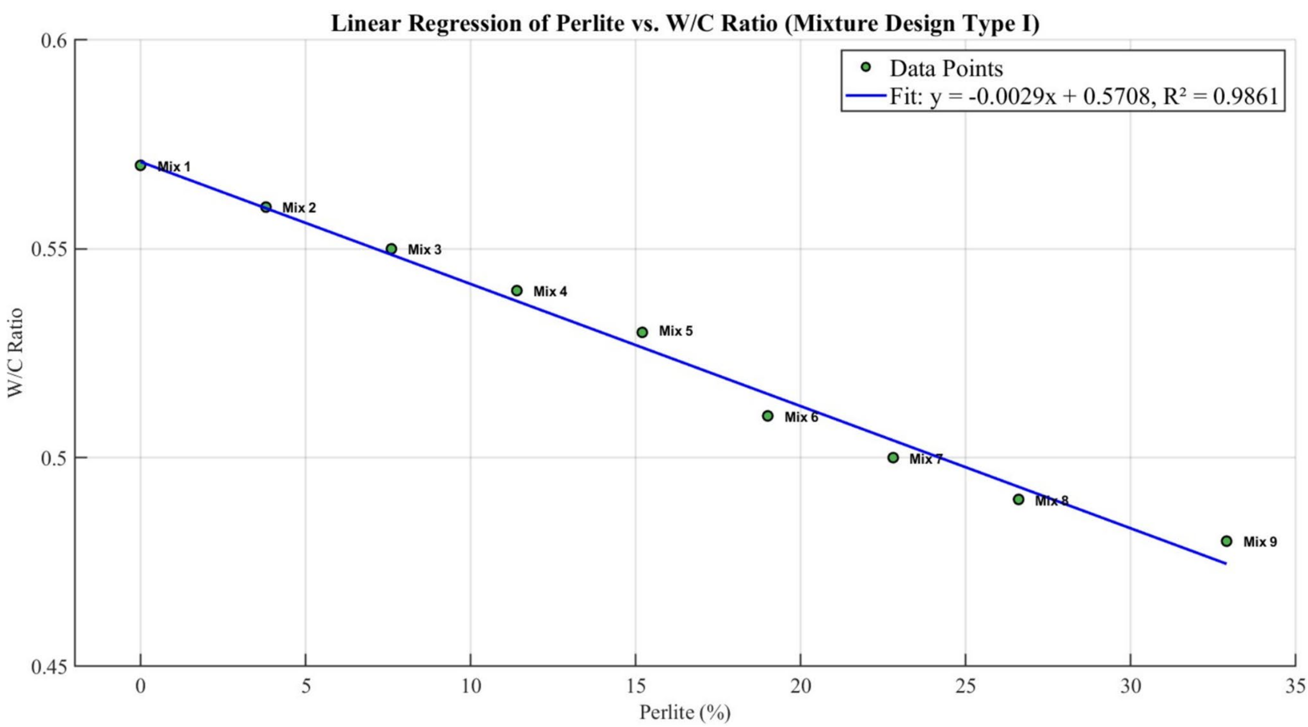

Fig. 2 Linear regression plot of perlite vs. (W/C) ratio for mixture design Type 1

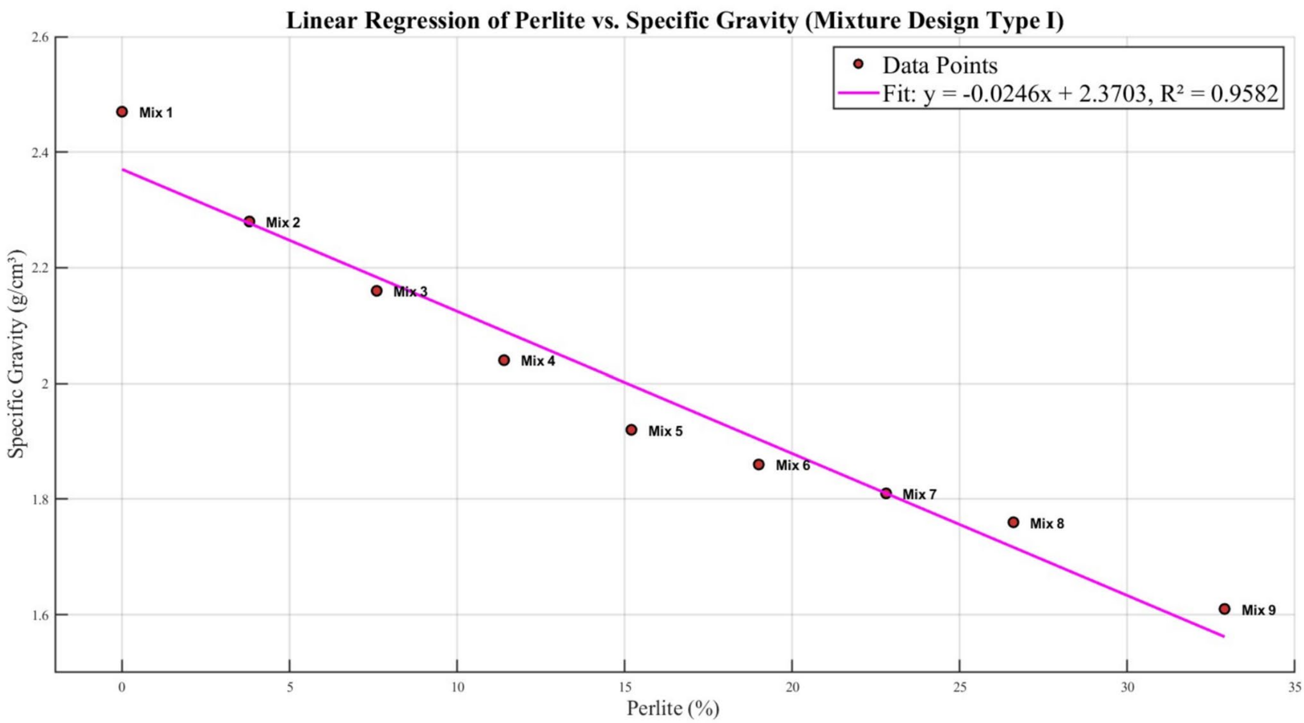

Fig. 3 Linear regression plot of perlite vs. specific gravity for mixture design Type 1

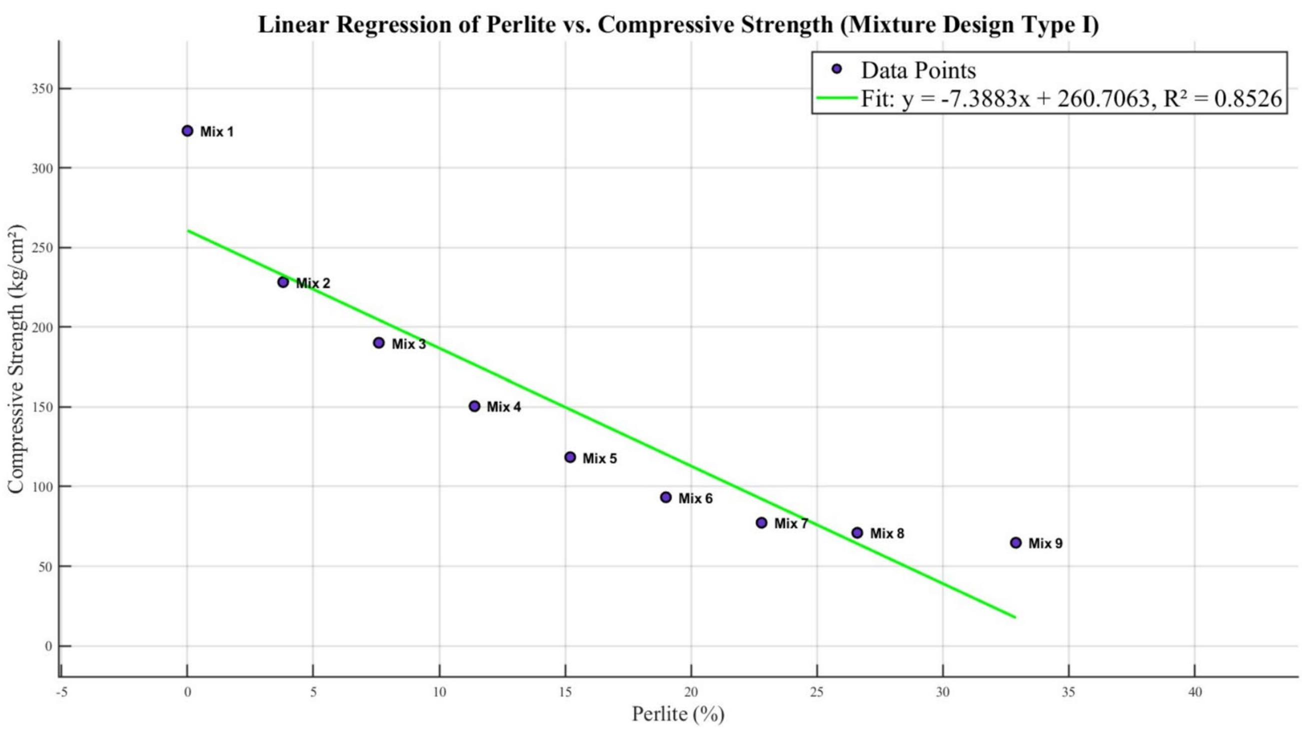

Fig. 4 Linear regression plot of perlite (%) vs. compressive strength (kg/cm^2) for mixture design Type 1

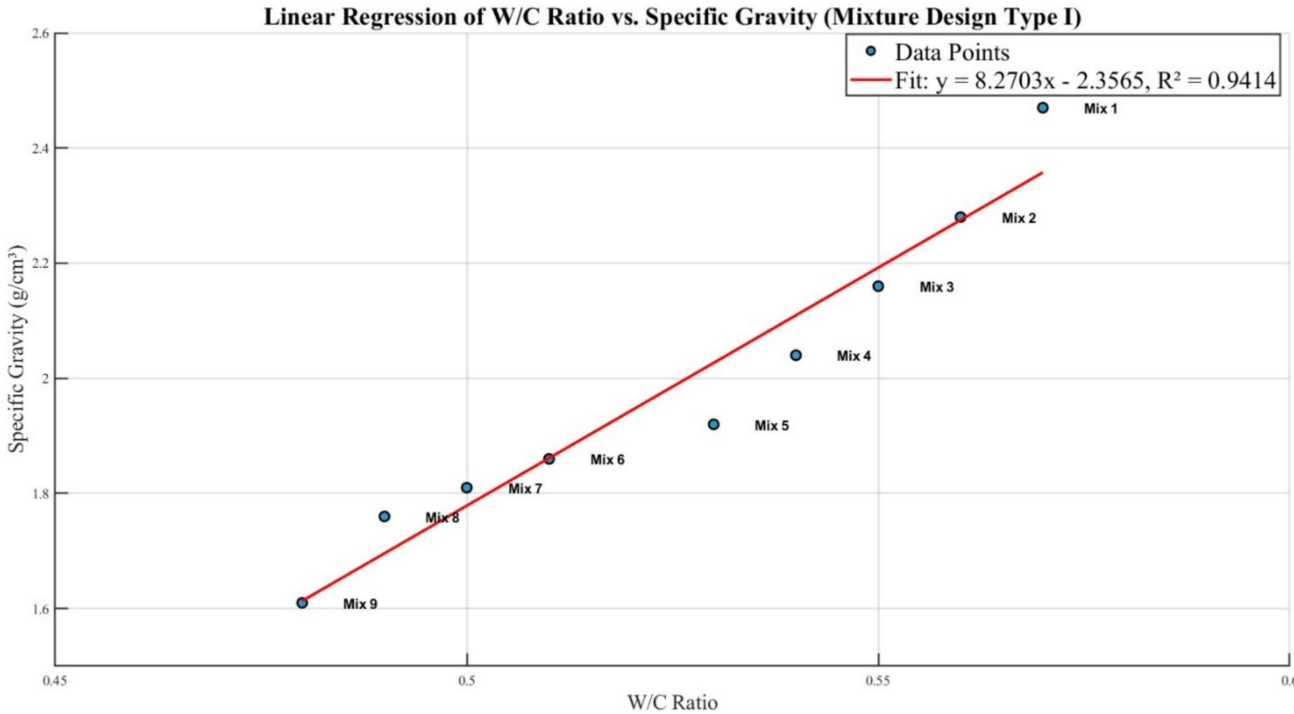

Fig. 5 Linear regression plot of W/C ratio (%) vs. specific gravity (g/cm^3) for mixture design Type 1

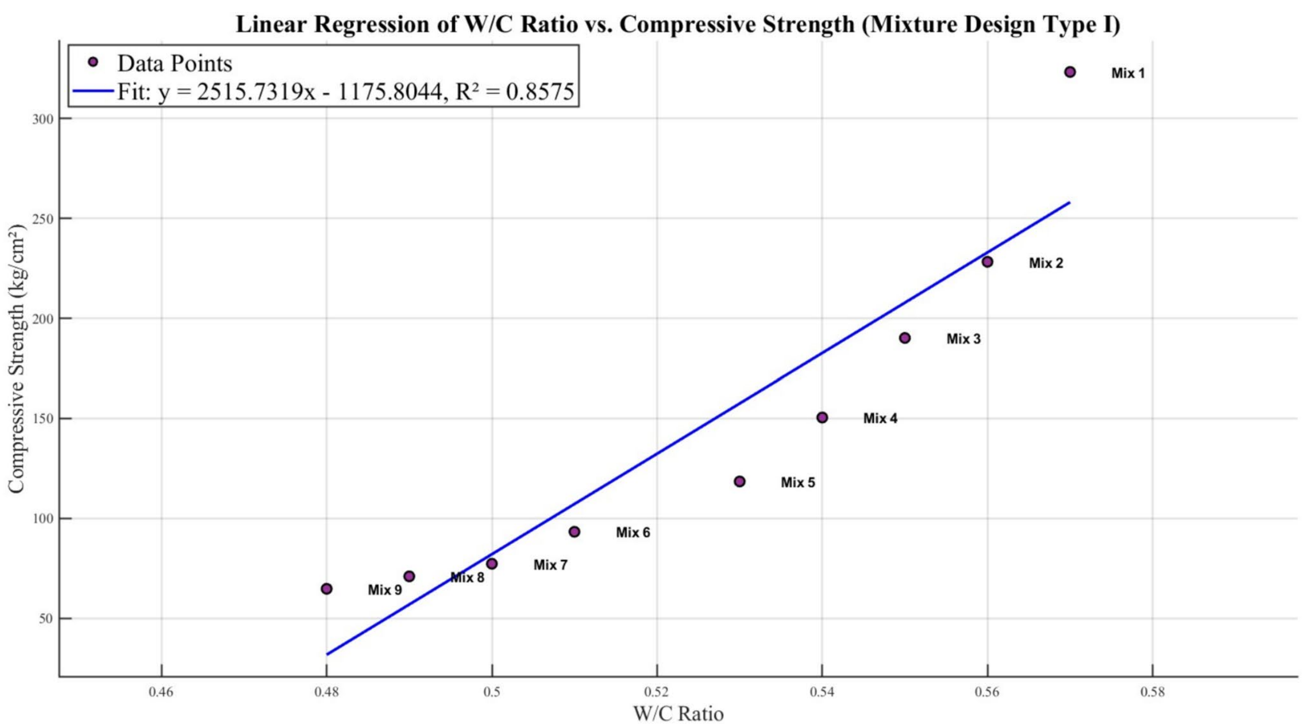

Fig. 6 Linear regression plot of W/C ratio (%) vs. compressive strength (kg/cm^2) for mixture design Type 1

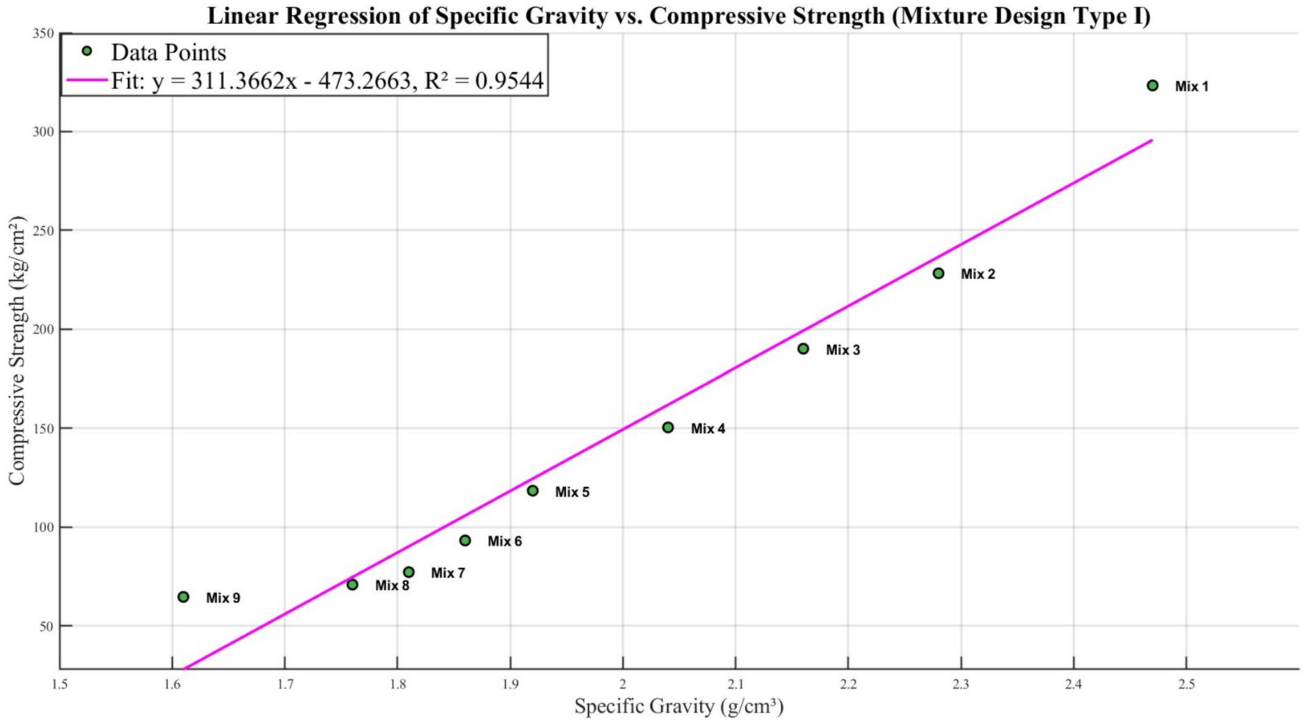

Fig. 7 Linear regression plot of specific gravity vs. compressive strength for mixture design Types I

Table 8 Volumetric proportions of mix design Type II (% by volume)

Mix no.	Leca (%)	Cement (%)	Water (%)	Sand (%)	Perlite (%)	W/C ratio
1	42.5	9.3	16.5	32.9	0.0	0.57
2	42.5	9.3	16.2	26.6	3.7	0.56
3	42.5	9.3	16.0	22.8	7.6	0.55
4	42.5	9.3	15.8	19.0	11.4	0.54
5	42.5	9.3	15.6	15.2	15.2	0.54
6	42.5	9.3	15.4	11.4	19.0	0.53
7	42.5	9.3	15.2	7.6	22.8	0.52
8	42.5	9.3	15.0	3.7	26.6	0.52

Compressive strength also correlates with W/C ratio (Fig. 6, $y=2515.7319x-1175.8044$, $R^2=0.8575$) and more strongly with specific gravity (Fig. 7, $y=311.3662x-473.2663$, $R^2=0.9544$), confirming density as a primary predictor of strength in perlite-modified concrete.

A consistent 2.5 cm slump across all mixes indicates that workability was maintained through controlled water adjustments, despite changes in the aggregate matrix. The high (R^2) values (0.8526–0.9861) demonstrate the predictability and controllability of perlite-based systems, with the perlite vs. W/C ratio regression showing the highest fit ($R^2=0.9861$), making it particularly valuable for mix optimization.

Compared to LECA-based systems, perlite causes a more pronounced reduction in both strength and density due to its finer texture and higher porosity, consistent with findings by (Dolatabad et al. 2020, Khoshvatan and Pauraminia 2021). Mix Design Type I is highly effective for producing lightweight concrete with enhanced durability (due to lower W/C), but its structural applicability diminishes beyond 20% perlite replacement. This design is best suited for semi-structural or non-load-bearing applications, such as partition walls, insulation layers, or precast panels, where weight reduction and thermal performance are prioritized over high compressive strength. The robust statistical models developed here provide engineers with reliable tools for tailoring concrete properties in sustainable construction practices.

Mix Design Type II investigates the influence of replacing fine aggregate with perlite in lightweight concrete incorporating Lightweight Expanded Clay Aggregate (LECA) as the coarse aggregate, with the aim of achieving ultra-low density while evaluating the associated mechanical trade-offs. As detailed in Table 8, nine mix proportions were formulated with a constant LECA content of 42.5% and cement at 9.3%, while perlite was incrementally increased from 0% to 33.4% at the expense of sand, which decreased

Table 9 Average results from nine experimental stages for mixture design Type II

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific Gravity (g/cm^3)	Compressive Strength (MPa)
1	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	13.97
2	42.5	27.7	9.3	4.2	16.2	0.55	2.5	1.68	12.38
3	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.37
4	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	9.90
5	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	8.53
6	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.20
7	42.5	5.7	9.3	27	15.2	0.52	2.5	1.06	6.59
8	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.59
9	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.62

Detailed individual specimen test results for Mix Designs 1–9 in Type II, including raw compressive strength data, have been moved to Appendix A as Table 51, 52, 53, 54, 55, 56, 57, 58, 59 to streamline the main text

from 31.7% to 0%. The water-to-cement (W/C) ratio was systematically reduced from 0.55 to 0.50 to maintain workability, which was consistently achieved at a 2.5 cm slump across all mixes, as confirmed by test results in Appendix A (Tables 51, 52, 53, 54, 55, 56, 57, 58, 59). The average results, summarized in Ta 35, reveal a dramatic reduction in specific gravity from 1.83 g/cm^3 (Mix 1) to 0.90 g/cm^3 (Mix 9)—a 51% decrease—driven by the replacement of dense sand (~2.65 g/cm^3) with highly porous perlite (~0.15 g/cm^3), while LECA (~0.5 g/cm^3) remained constant. Concurrently, 28-day compressive strength declined from 13.97 MPa to 6.62 MPa, representing a 52.7% reduction due to perlite's low particle strength, weak interfacial bonding with the cement matrix, and disruption of mechanical interlocking within the microstructure. Notably, the rate of strength loss slows at higher perlite contents (above 27%), with a slight rebound in Mix 9 (6.62 MPa vs. 6.59 MPa in Mix 8), attributed to improved particle packing or reduced internal stress concentrations at full sand replacement. This observation aligns with (VarshaSri et al. 2024), who reported that high-volume perlite can enhance homogeneity in ultra-lightweight systems despite low strength. The consistent slump across all mixes indicates that workability can be effectively controlled through incremental water reduction, even with high perlite content, which exhibits low water absorption compared to other lightweight aggregates like LECA. However, the diminishing returns in strength highlight the limitations of perlite in load-bearing applications. When compared to Mix Design Type I (gravel-based), Type II achieves significantly lower densities (0.90 vs. 1.61 g/cm^3 at maximum perlite), making it more suitable for non-structural applications such as insulation panels, thermal barriers, or lightweight fill materials (Al-Dikheeli et al. 2022; Sonia et al. 2016). However, Type I retains higher initial strength (31.61 MPa vs. 13.97 MPa), favoring applications where structural integrity is prioritized. The results confirm that LECA-perlite combinations enable extreme weight reduction but at the cost of mechanical performance, with perlite acting as the dominant factor in both density and strength reduction. This design is best suited for applications where ultra-low density and thermal insulation are prioritized over structural capacity and provides a reliable framework for tailoring lightweight concrete properties in energy-efficient and sustainable construction systems (see Tables 9, 10).

Table 10 Standard deviation for mix Type I

Mix design	Mean compressive strength (MPa)	Standard deviation (MPa)
1	31.595	1.633
2	22.387	1.187
3	18.652	1.039
4	14.763	1.115
5	11.621	0.437
6	9.150	0.649
7	7.579	0.487
8	6.963	0.329
9	6.355	0.251

A comprehensive statistical and regression analysis was conducted to evaluate the influence of perlite content on the physical and mechanical properties of Mix Design Type II, where perlite progressively replaced sand in a LECA-based lightweight concrete system. The standard deviation of compressive strength, calculated using Eq. (1):

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

where σ is the standard deviation, n is the number of samples, xi is the individual strength value, and x^{-} is the mean strength, was determined for each mix. As shown in Table 11, the standard deviation decreased from 0.55 MPa in Mix 1 (0% perlite) to 0.22 MPa in Mix 7 (27.3% perlite), indicating improved consistency in strength with increasing perlite content. This trend suggests that the uniform porosity and particle distribution of perlite, combined with the stable framework provided by LECA (~0.5 g/cm^3), enhance mix homogeneity, despite minor fluctuations at very high perlite levels (Mixes 8–9). A similar pattern was observed in Mix Design Type I (Table 10), though with higher overall variability due to the greater density contrast between gravel (~2.65 g/cm^3) and perlite.

The relationship between perlite content and specific gravity in Mix Design Type II is illustrated in Fig. 8, based on experimental data from Tables 12 and 13. The specific gravity decreases sharply from 1.83 g/cm^3 at 0% perlite to 0.90 g/cm^3 at 33.4% perlite, representing a 51% reduction. This decline is notably steeper than in Mix Design Type I, where specific gravity decreased from 2.47 g/cm^3 to 1.61 g/cm^3 (a 34.8% reduction). The enhanced density reduction in Type II is attributed to the synergistic effect of low-density Lightweight Expanded Clay Aggregate (LECA) and highly porous perlite (~0.15 g/cm^3), which together significantly reduces the solid phase mass of the composite.

A strong negative correlation between perlite content and specific gravity is confirmed by the linear regression equation $y = -0.0270x + 1.8015$ (Fig. 9, $R^2 = 0.9828$). This model indicates that 98.28% of the variability in specific gravity is explained by perlite substitution. The slope of -0.0270 is steeper than that of Type I (-0.0246), highlighting the amplified lightweighting effect of combining LECA and perlite in Type II. These findings underscore the effectiveness of

Table 11 Standard deviation for mix Type II

Mix design	Mean compressive strengt (MPa)	Standard deviation (MPa)
1	13.97	0.55
2	12.40	0.45
3	11.37	0.27
4	9.90	0.57
5	8.53	0.46
6	7.20	0.32
7	6.59	0.22
8	6.66	0.23
9	6.62	0.23

Table 12 Average density (g/cm^3) vs. perlite percentage for mix design Types I

Mix design	Perlite (%)	Density (g/cm^3)
1	0.0	2.47
2	3.8	2.28
3	7.6	2.16
4	11.4	2.04
5	15.2	1.92
6	19.0	1.86
7	22.8	1.81
8	26.6	1.76
9	32.9	1.61

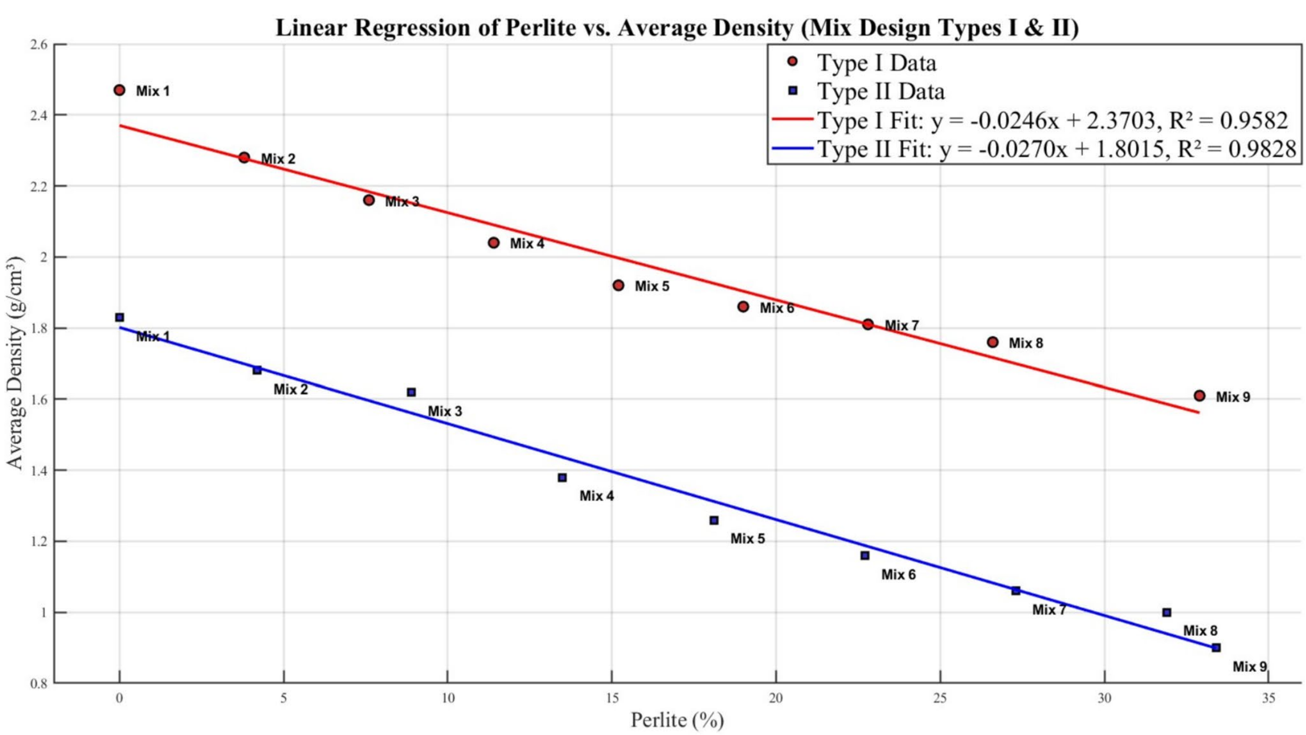

Fig. 8 Average density (g/cm^3) vs. perlite percentage for both mix design Types I & II

Table 13 Average density (g/cm^3) vs. perlite percentage for mix design Types II

Mix design	Perlite (%)	Density (g/cm^3)
1	0.0	1.83
2	4.2	1.68
3	8.9	1.62
4	13.5	1.38
5	18.1	1.26
6	22.7	1.16
7	27.3	1.06
8	31.9	1.00
9	33.4	0.90

dual lightweight aggregates in achieving significant density reductions, making Mix Design Type II particularly suitable for applications prioritizing low weight, such as insulation layers or non-structural elements.

Compressive strength, as depicted in Fig. 10 and summarized in Tables 14 and 15, decreases from 13.97 MPa to 6.62 MPa with increasing perlite content from 0% to 33.4% in Mix Design Type II. The regression model (Fig. 11, $y=-2.3052x+135.2706$, $R^2=0.9497$) indicates a strong negative correlation between perlite content and compressive strength. This strength loss is less severe than in Mix Design Type I ($R^2=0.8526$, slope = -0.7388), reflecting the stabilizing role of Lightweight Expanded Clay Aggregate (LECA) compared to the gravel-based system in Type I. The convergence of compressive strength values at high perlite levels (~6.4–6.7 MPa) in both mix designs suggests that beyond a critical perlite threshold, the mechanical properties of the fine aggregate dominate over the coarse aggregate type. Further regression analyses reveal high predictability in mix behavior. The relationship between perlite content and water demand (Fig. 12, $y=-0.0470x+16.4464$, $R^2=0.9935$) demonstrates that perlite's internal porosity significantly reduces free water requirements, with each 1% increase in perlite reducing water demand by approximately 0.047%. This is supported by a strong correlation between perlite content and water-to-cement (W/C) ratio (Fig. 13, $y=-0.0014x+0.5526$, $R^2=0.9536$), where W/C decreases from 0.55 to 0.51 as perlite increases from 0% to 33.4%. The specific gravity–compressive strength relationship (Fig. 14, $y=85.8114x-19.1555$, $R^2=0.9688$) confirms that density is a key predictor of strength in lightweight concrete systems, with specific gravity ranging from 1.83 g/cm^3 to 0.90 g/cm^3. Similarly, the specific gravity–compressive strength relationship in Fig. 15 ($y=85.8114x+-19.1555$, $R^2=0.9406$) shows a slightly lower but still strong correlation, indicating that 94.06% of the variability in compressive strength is explained by specific gravity. The decrease in (R^2) from 0.9688 (Fig. 14) to 0.9406 (Fig. 15) suggests a minor reduction in model fit due to differences in data points, experimental conditions, or a narrower range of specific gravity values in Fig. 15. Compared to other regressions, the (R^2) of 0.9406 in Fig. 15 is lower than perlite vs. water demand ($R^2=0.9935$), perlite vs. specific gravity ($R^2=0.9828$), and Fig. 14 ($R^2=0.9688$), but higher than perlite vs. W/C

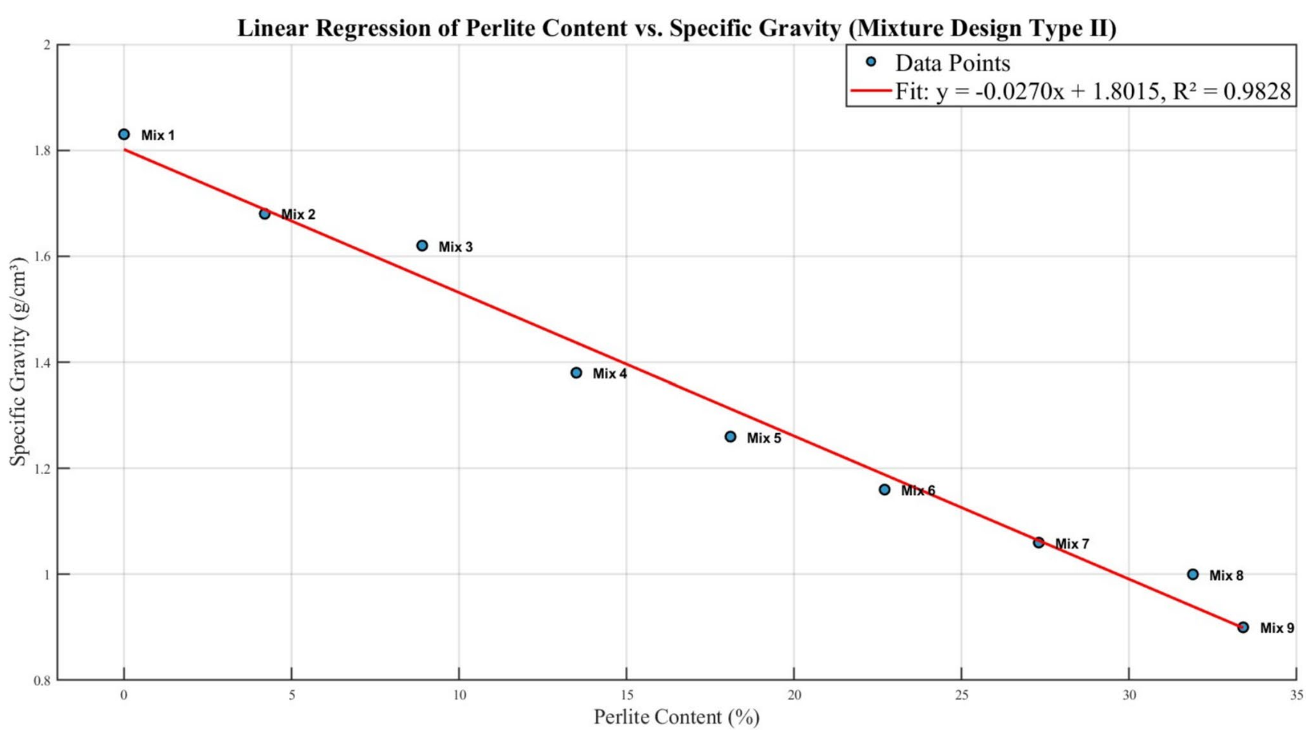

Fig. 9 Linear regression plot of perlite (%) vs. specific gravity for mixture design Type II

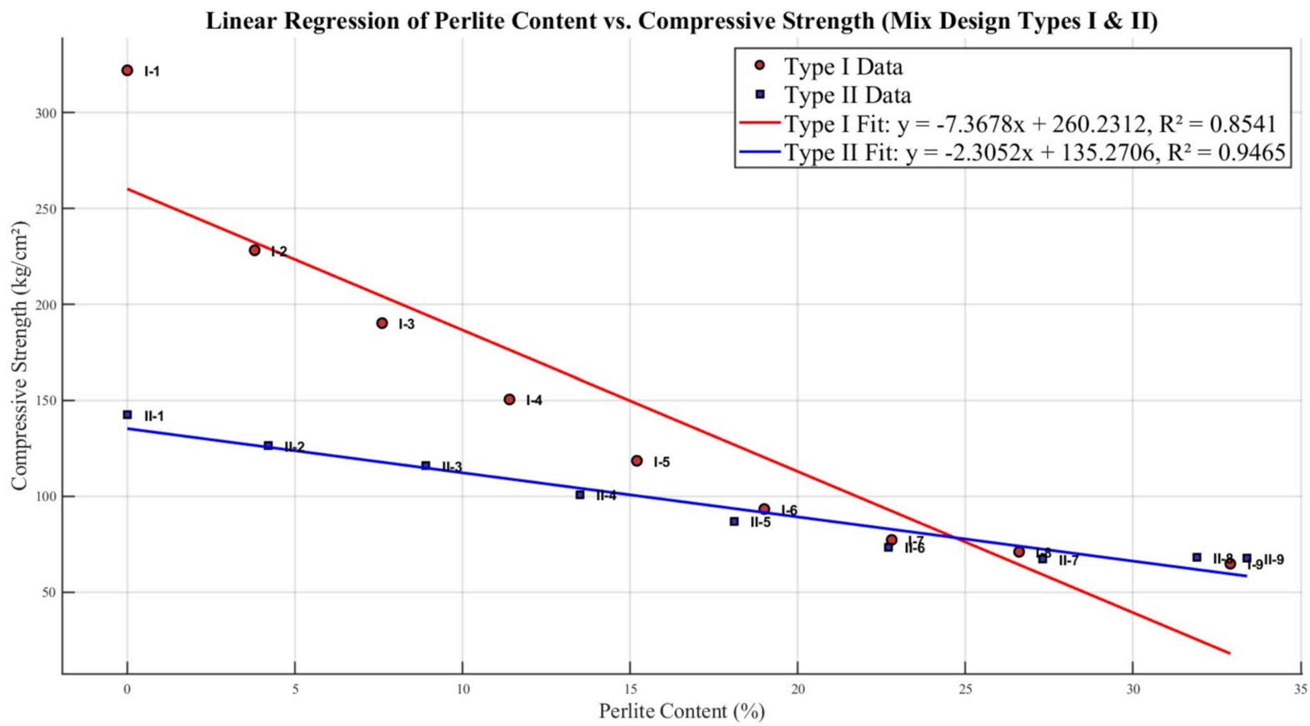

Fig. 10 Average compressive strength (kg/cm^2) vs. perlite content for both mix design Types I & II

Table 14 Compressive strength vs. perlite content Type I

Mix design	Perlite (%)	Compressive strength (MPa)
1	0.0	31.59
2	3.8	22.38
3	7.6	18.65
4	11.4	14.76
5	15.2	11.62
6	19.0	9.15
7	22.8	7.57
8	26.6	6.96
9	32.9	6.35

Table 15 Compressive strength vs. perlite content Type II

Mix design	Perlite (%)	Compressive strength (MPa)
1	0.0	13.97
2	4.2	12.38
3	8.9	11.37
4	13.5	9.90
5	18.1	8.53
6	22.7	7.20
7	27.3	6.59
8	31.9	6.66
9	33.4	6.62

(R^2 = 0.9536), perlite vs. compressive strength (R^2 = 0.9497), and W/C vs. compressive strength (R^2 = 0.8625). This indicates that while specific gravity is a strong predictor of strength, other factors, such as aggregate bonding or matrix variability, introduce slightly more variability in Fig. 15's dataset. The W/C vs. compressive strength regression (Fig. 16, $y = 1546.2x — 721.9$, R^2 = 0.8625) shows lower precision, indicating that while W/C is adjusted to maintain consistent workability (slump = 2.5 cm), it is secondary to aggregate composition in controlling strength. These findings align with studies by (Dolatabad et al. 2020, Khoshvatan and Pauraminia 2021 and Othman et al. 2020), which highlight the role of porous aggregates in reducing density and water demand while noting the mechanical limitations of perlite. The high (R^2) values in Type II regressions—particularly for perlite vs. water demand (R^2 = 0.9935) and perlite vs. specific gravity (R^2 = 0.9828)—demonstrate that LECA-perlite systems offer greater predictability and control compared to gravel-perlite mixes in Type I. This makes Mix Design Type II particularly suitable for applications requiring ultra-low density and consistent rheology, such as insulation blocks, non-load-bearing panels, or thermal barriers in sustainable construction. While compressive strength is limited, the high degree of control and repeatability support the use of Type II in precast and industrial applications where dimensional stability and thermal performance are prioritized over structural capacity.

A systematic experimental study was conducted to investigate the effect of replacing natural gravel with Lightweight Expanded Clay Aggregate (LECA) on the density, compressive strength and workability of concrete, while maintaining constant sand (30.2%) and cement (9.3%) contents. Seven mix proportions were designed, with LECA

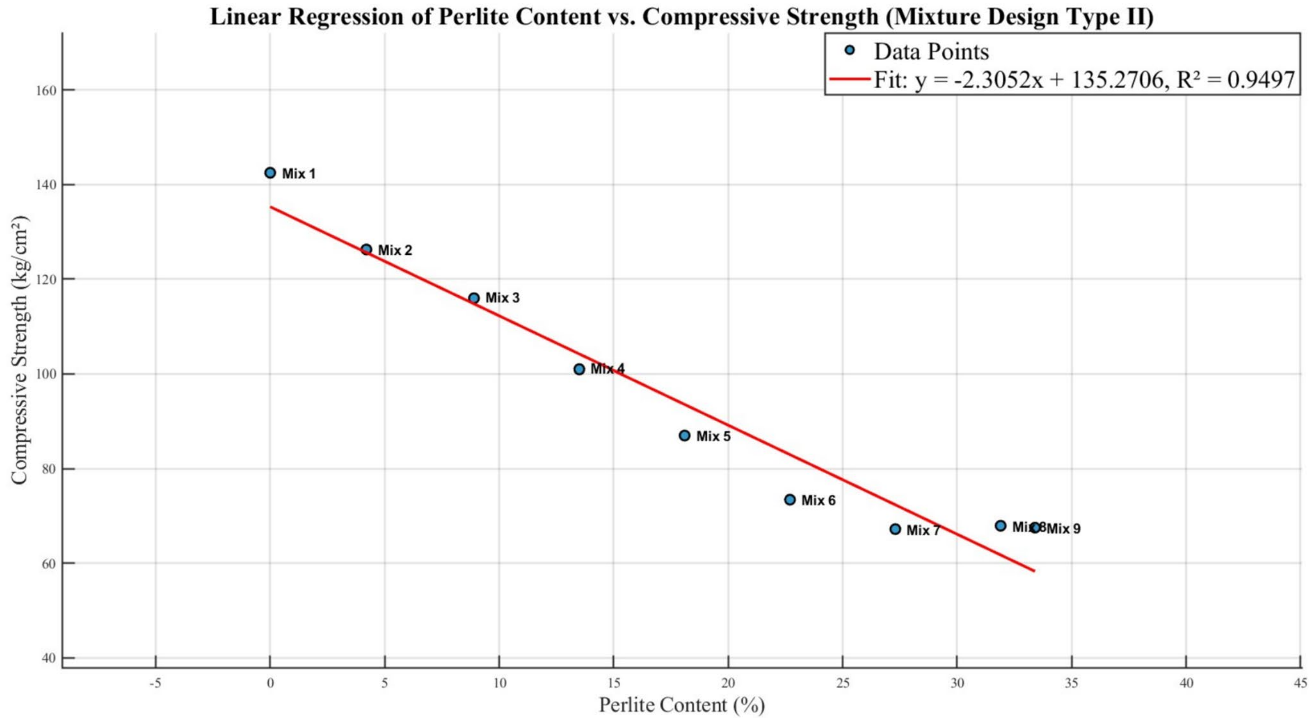

Fig. 11 Linear regression plot of perlite (%) vs. compressive

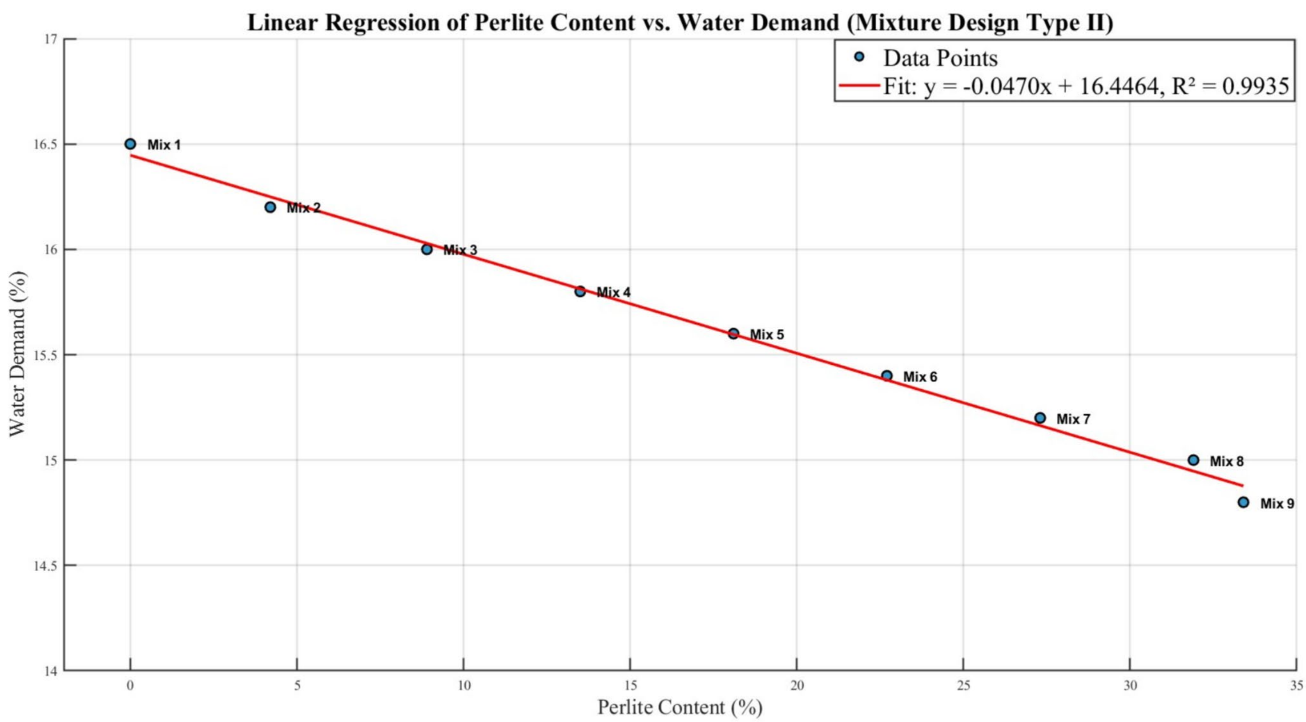

Fig. 12 Linear regression plot of perlite (%) vs. water demand (%) for mixture design Type II

content increasing incrementally from 0 to 44% by volume, accompanied by a corresponding reduction in gravel content from 42.5 to 0% and a gradual decrease in water content from 18.0 to 16.5% to maintain adequate workability and hydration (Table 16). The water-to-cement (W/C) ratio was thus reduced from 0.61 to 0.56 across the series. All mixtures exhibited a consistent slump of 2.5 cm, indicating that workability was effectively controlled despite the

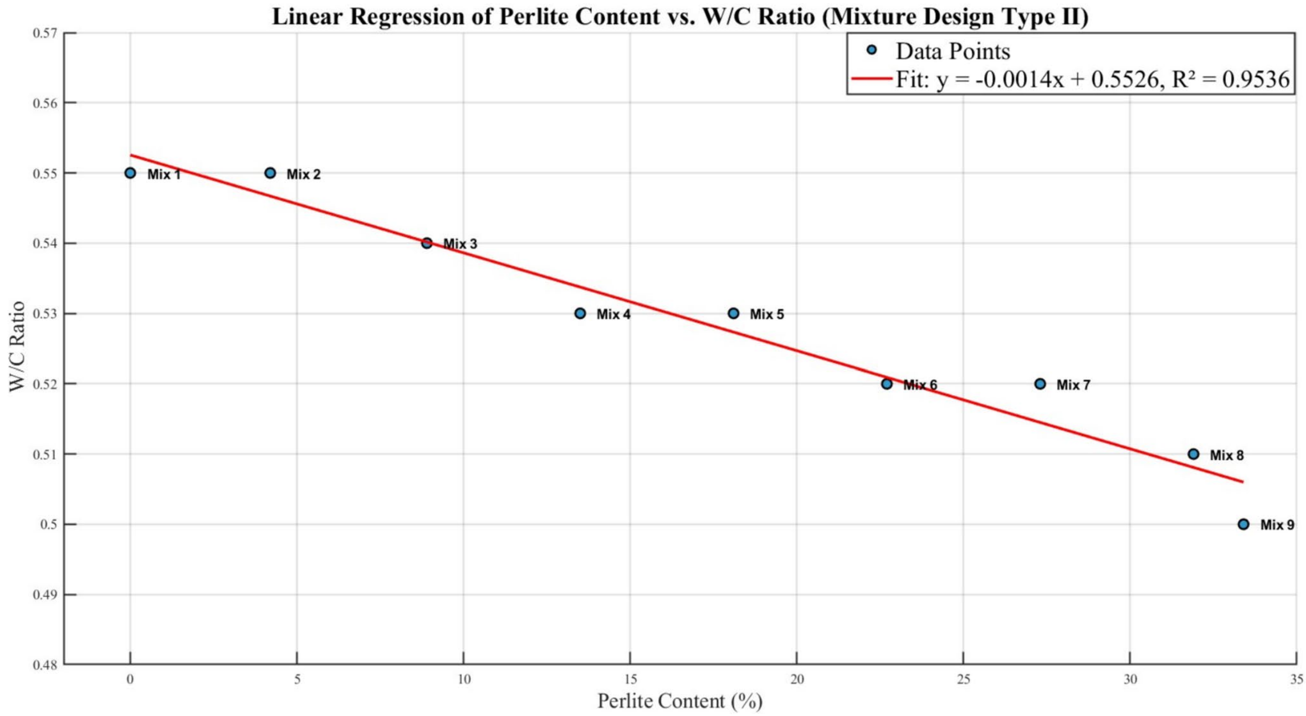

Fig. 13 Linear regression plot of perlite (%) vs. W/C ratio for mixture design Type II strength (kg/cm^2) for mixture design Type II

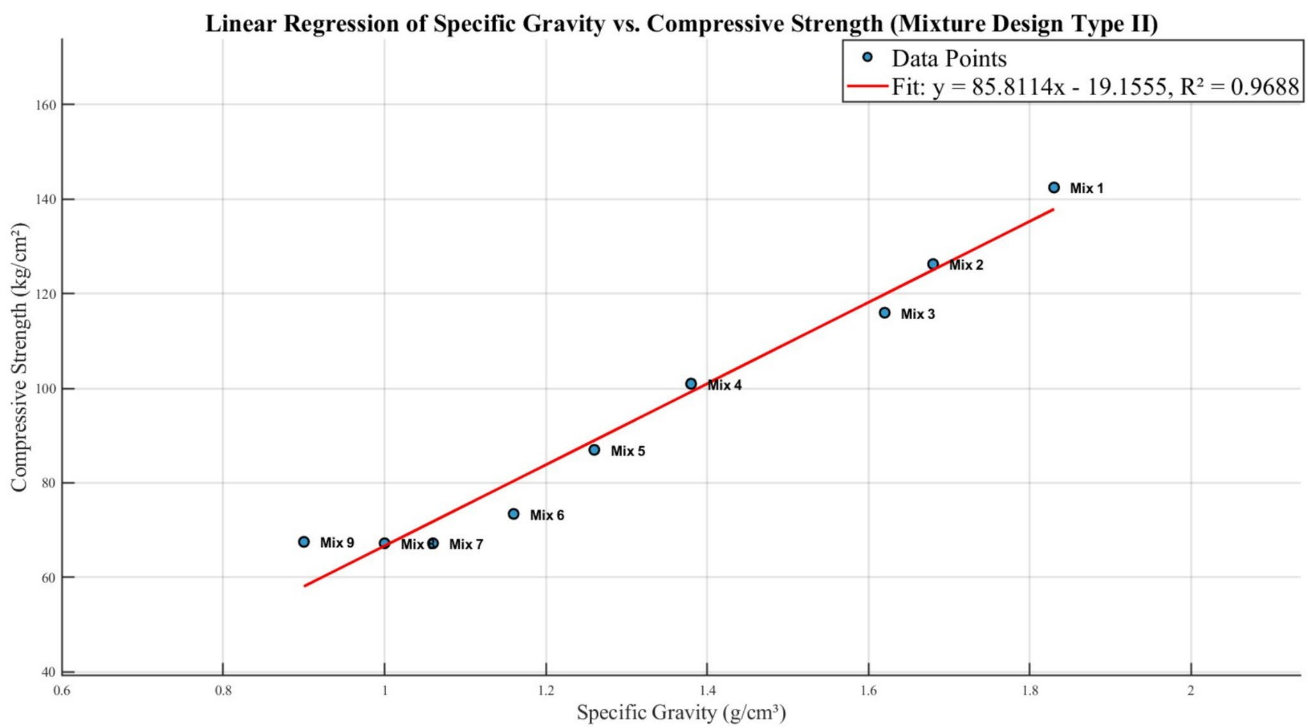

Fig. 14 Linear regression plot: specific gravity (g/cm^3) vs compressive strength (kg/cm^2) (mixture design type II)

increasing use of LECA, which typically exhibits higher water absorption. The 28-day compressive strength and specific gravity results, consolidated in Table 17, reveal a significant trade-off between lightweight characteristics and mechanical performance. Specific gravity decreased linearly from 2.47 g/cm^3 (Mix 1) to 1.83 g/cm^3 (Mix 7), representing a 26% reduction in density due to the substitution of dense gravel (~2.65 g/cm^3) with lightweight LECA (~0.5 g/

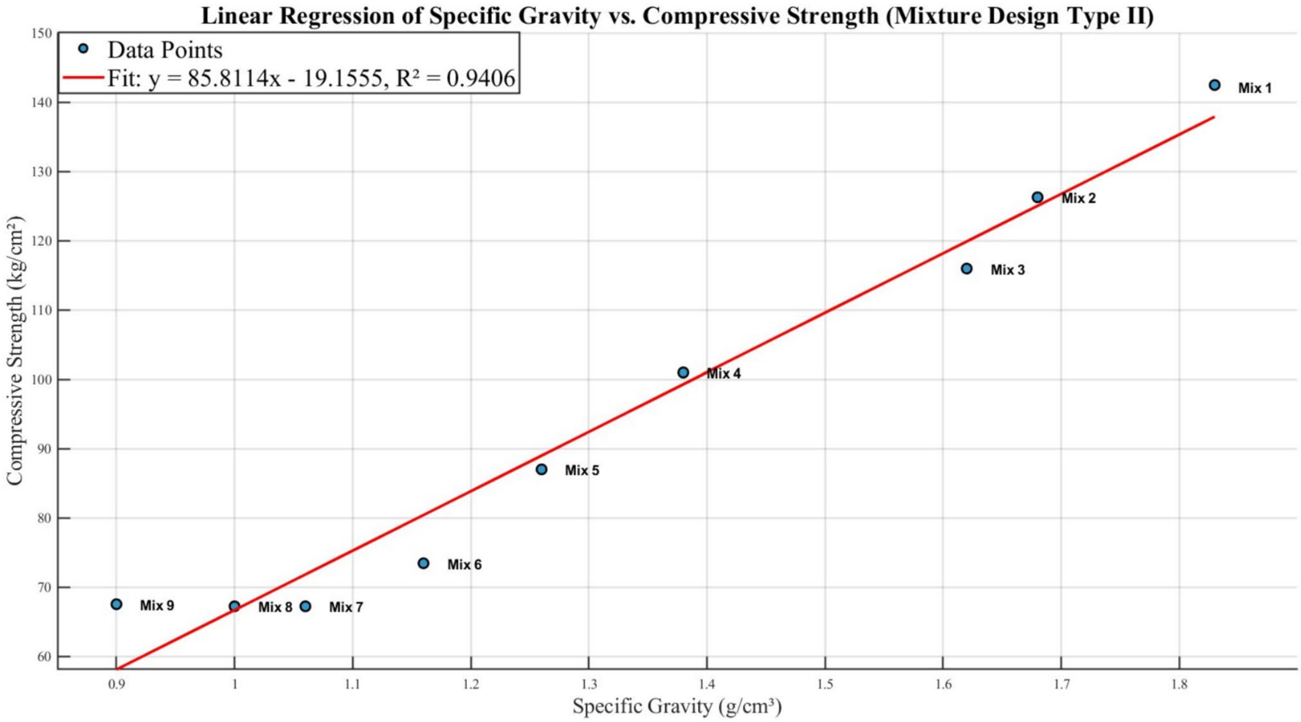

Fig. 15 Linear regression plot specific gravity (g/cm^3) vs compressive strength (kg/cm^2) (mixture design Type II)

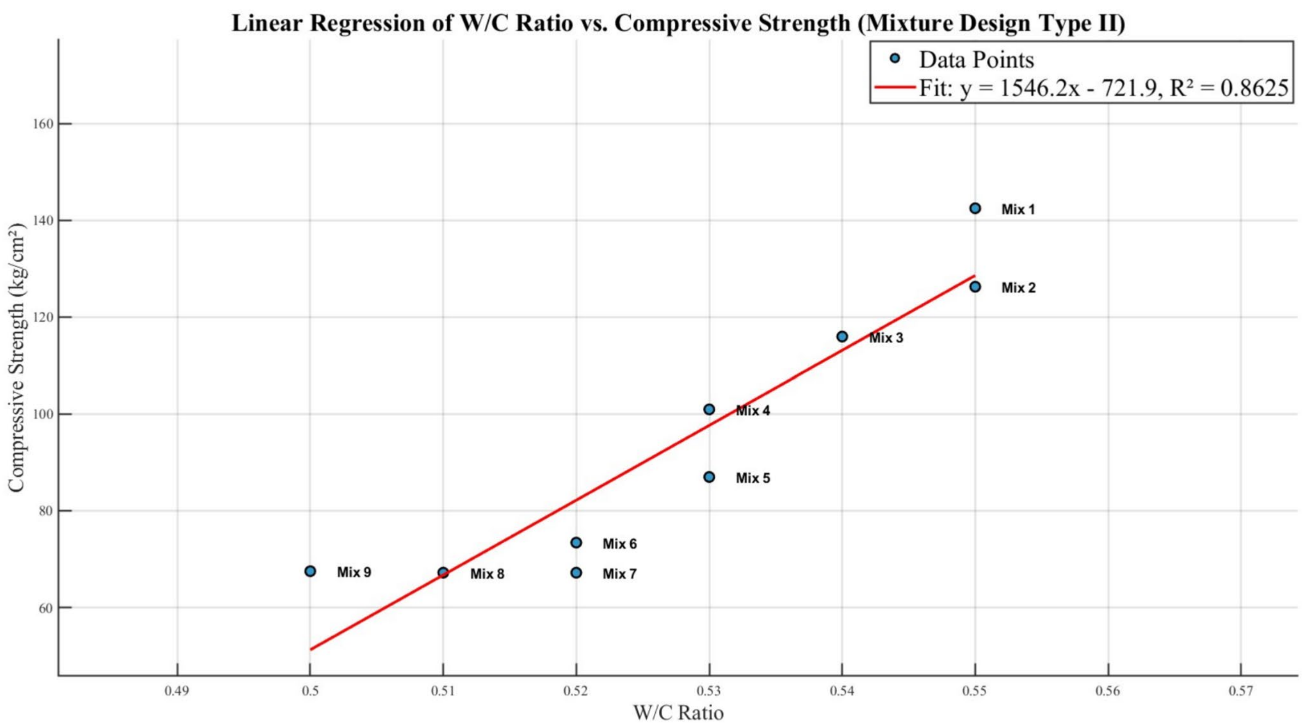

Fig. 16 Linear regression plot of W/C ratio vs. compressive strength (kg/cm^2) for mixture design Type II

cm^3). Concurrently, compressive strength declined from 31.59 MPa to 16.09 MPa—a reduction of nearly 49%—demonstrating the dominant influence of aggregate strength on the overall mechanical behavior of the composite. This trend is particularly pronounced beyond 28% LECA replacement (Mix 5 onward), where the rate of strength loss increases, suggesting a practical threshold for structural applications. Although the progressive reduction in

Table 16 Volumetric proportions of mix design Type III (% by volume)

Mix no.	Gravel (%)	Cement (%)	Water (%)	Sand (%)	Leca (%)	W/C ratio
1	42.5	9.3	18.0	30.2	0.0	0.60
2	35.7	9.3	17.8	30.2	7.0	0.59
3	28.9	9.3	17.6	30.2	14.0	0.58
4	22.2	9.3	17.3	30.2	21.0	0.57
5	15.5	9.3	17.0	30.2	28.0	0.56
6	8.7	9.3	16.8	30.2	35.0	0.56
7	0.0	9.3	16.5	30.2	44.0	0.55

Detailed per-specimen test results for Mix Designs 1–7 in Type III have been moved to Appendix A as Tables 60, 61, 62, 63, 64, 65, 66 to streamline the main text

Table 17 Average results from seven experimental stages for mix design Type III

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	31.59
2	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	28.75
3	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	26.99
4	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	25.25
5	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	22.40
6	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	19.41
7	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	16.09

W/C ratio improved cement hydration and paste density, it was insufficient to offset the weakening effect of the porous LECA particles and the less efficient load transfer within the matrix. The observed strength degradation aligns with findings reported by Ningampalli et al. (2021) and Podnar and Kravanja (2025), who noted similar reductions in compressive strength at high LECA replacement levels. Furthermore, the results are consistent with Al-Dikheeli et al. (2016) and Olusola and Babafemi (2013), who observed that up to 25% replacement of coarse aggregate with lightweight aggregates retains over 80% of the control strength—closely matching the performance of Mixes 3 and 4 in this study (85% and 80% respectively). Based on these findings, mixes 1–4 (up to 21% LECA) are suitable for semi-structural applications where moderate weight reduction is desired without severe strength compromise, while mixes 5 to 7 (≥28% LECA) are better suited for non-load-bearing elements such as partition walls, insulation blocks, or precast panels, where low density is prioritized. This graded mix design approach provides a practical framework for tailoring concrete properties to specific engineering requirements, balancing structural performance with weight efficiency.

The experimental investigation of Mix Design Type III, where gravel was progressively replaced with Lightweight Expanded Clay Aggregate (LECA) while maintaining constant sand (30.2%) and cement (9.3%) content, demonstrates a highly predictable transition from conventional structural concrete to lightweight non-structural concrete. As summarized in Table 17 and illustrated in Figs. 17, 18, increasing LECA content from 0 to 44% reduced specific gravity from 2.47 g/cm^3 to 1.83 g/cm^3 and decreased 28-day compressive strength from 31.59 MPa to 16.09 MPa. Workability was maintained at a consistent 2.5 cm slump across all mixtures through incremental water content adjustments, confirming the feasibility of uniform rheological properties despite high-volume lightweight aggregate substitution.

A strong positive correlation between water-to-cement (W/C) ratio and specific gravity (Fig. 17, $y = 11.6563x - 4.7163$, $R^2 = 0.9645$) reflects the dominant role of aggregate density in determining overall mix density. As LECA (~0.5 g/cm^3) replaces gravel (~2.65 g/cm^3), the reduction in solid phase mass directly lowers specific gravity, aligning with findings by Zukri et al. (2018) and Al-Dikheeli et al. (2022). Similarly, a robust linear relationship between W/C ratio and compressive strength (Fig. 19: $y = 2789.8265x - 1393.6666$, $R^2 = 0.9719$) highlights the influence of aggregate type on mechanical performance. The ($R^2 = 0.9719$) indicates that 97.19% of compressive strength variability is explained by W/C ratio, reflecting a strong predictive model. Compared to other regressions, this (R^2) is slightly lower than LECA vs. compressive strength ($R^2 = 0.9927$) and LECA vs. water demand ($R^2 = 0.9959$), but higher than LECA vs. W/C ($R^2 = 0.9790$), specific gravity vs. compressive strength ($R^2 = 0.9875$), and specific gravity vs. LECA content ($R^2 = 0.9891$). The slightly lower R^2 in Fig. 19 compared to Figs. 20 and 21 suggests that while the W/C ratio significantly influences strength, LECA content is a more direct predictor due to its impact on aggregate matrix

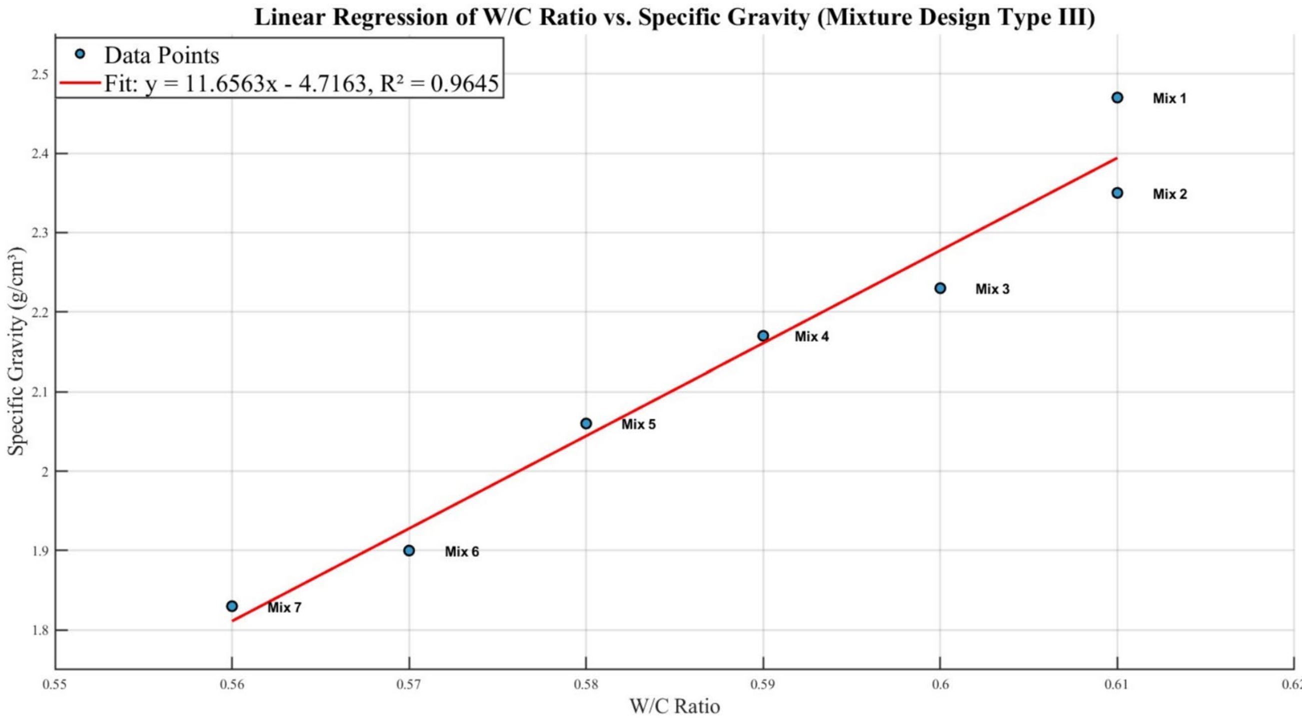

Fig. 17 Linear regression plot W/C ratio vs specific gravity (g/cm^3) (mixture design Type III)

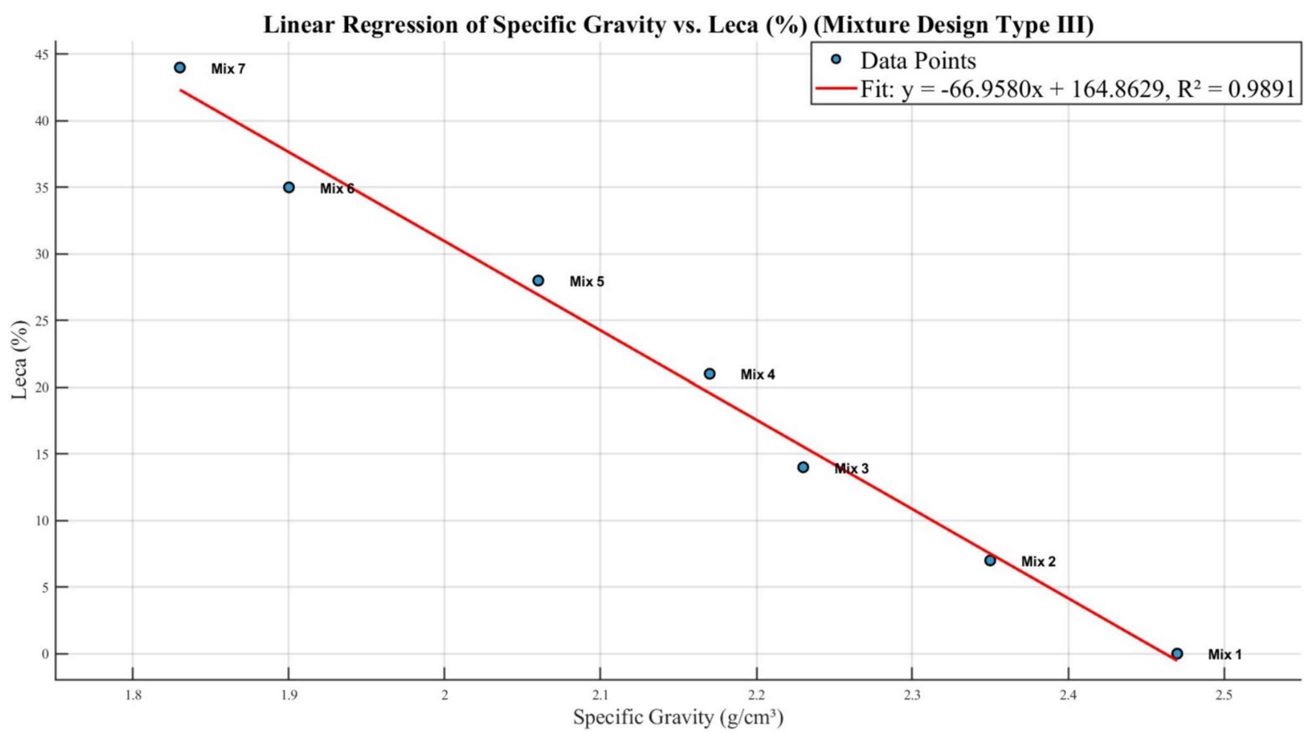

Fig. 18 Linear regression plot specific gravity (g/cm^3) vs leca (%) (mixture design Type III)

properties. However, the higher R^2 compared to Fig. 17 indicates that the W/C ratio is a stronger predictor of strength than of specific gravity, due to its role in cement hydration and paste strength.

The most significant regression model is between LECA content and compressive strength (Fig. 20, $y=-3.5279x+323.4399$, $R^2=0.9927$), that 99.27% of strength variability is explained by LECA substitution.

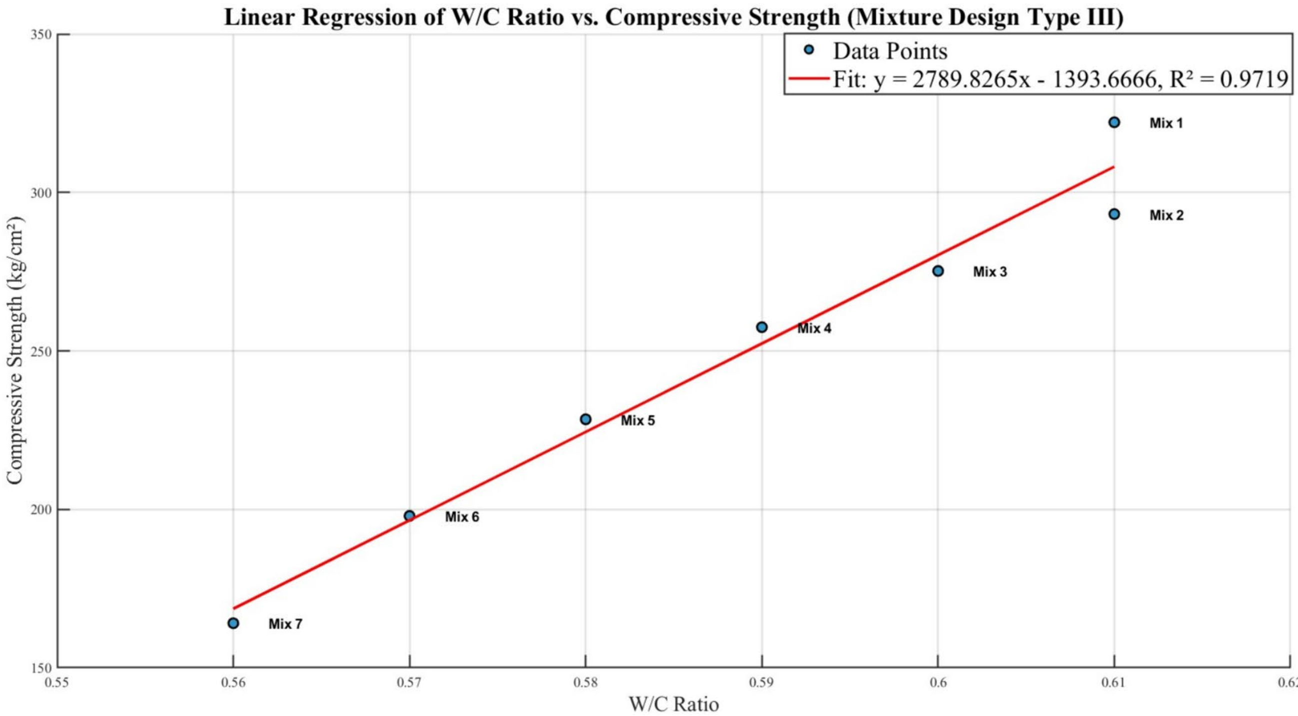

Fig. 19 Linear regression plot W/C ratio vs compressive strength (mixture design Type III)

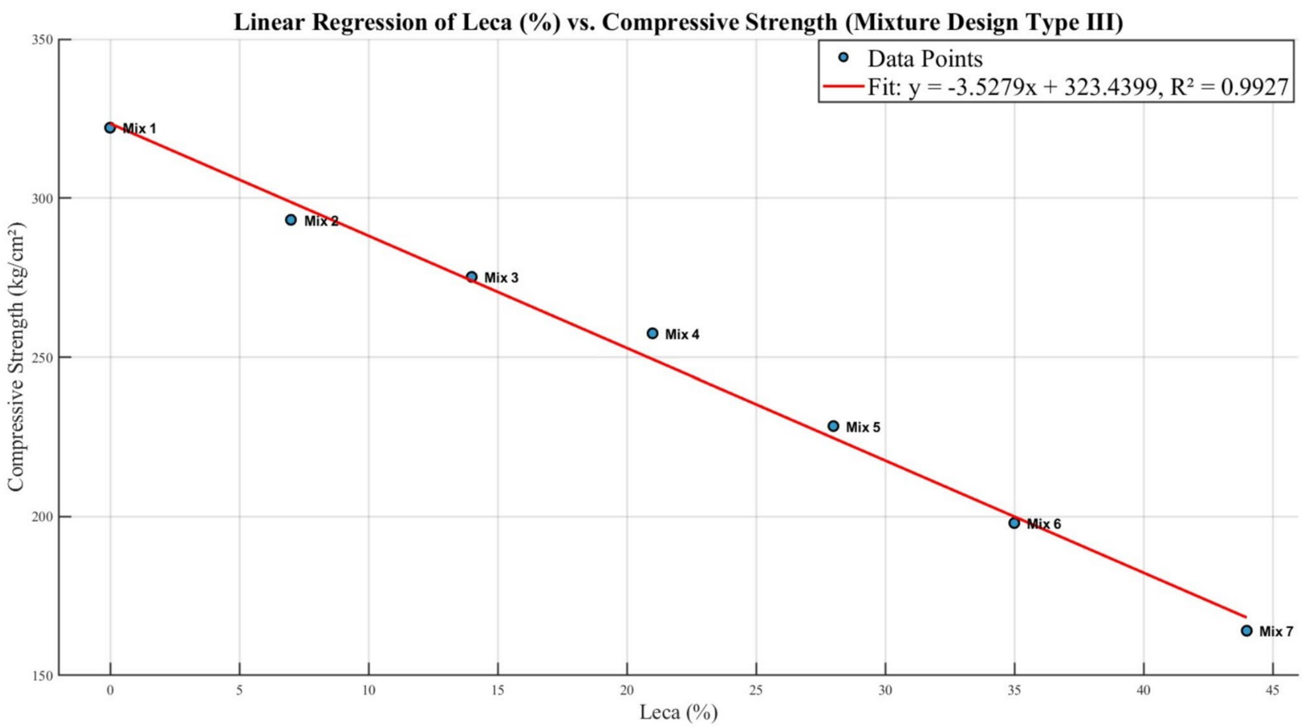

Fig. 20 Linear regression plot Leca (%) vs compressive strength (kg/cm^2) (mixture design Type III)

The slope of -0.3528 MPa per % LECA suggests a gradual strength decline, less severe than in perlite-based systems (e.g., Mix Design Type I, slope = -0.7388), due to LECA's superior particle integrity and surface characteristics, as supported by VarshaSri et al. (2024). Strong negative correlations between LECA content and W/C ratio (Fig. 22, $y = -0.0012x + 0.6149$, $R^2 = 0.9790$) and water demand (Fig. 21, y = -0.0351x + 18.0335, $R^2 = 0.9959$) highlight

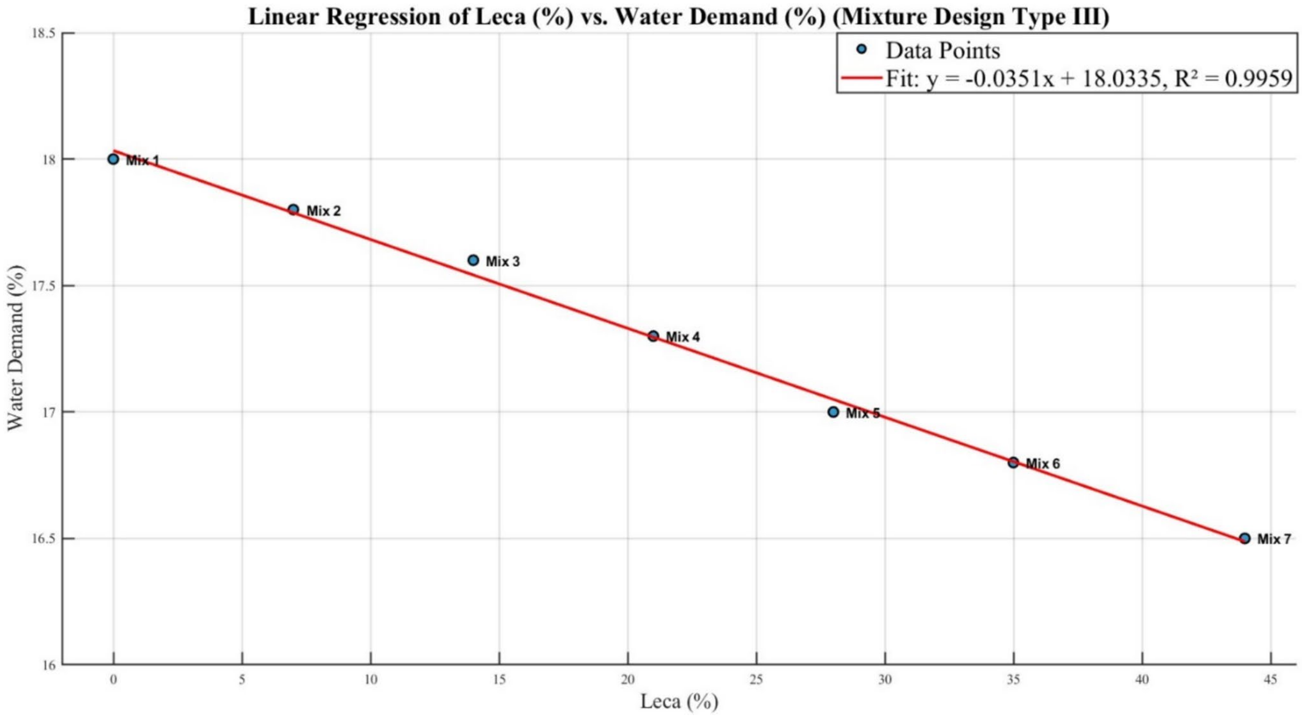

Fig. 21 Linear regression plot Leca (%) vs water demand (%) (mixture design Type III)

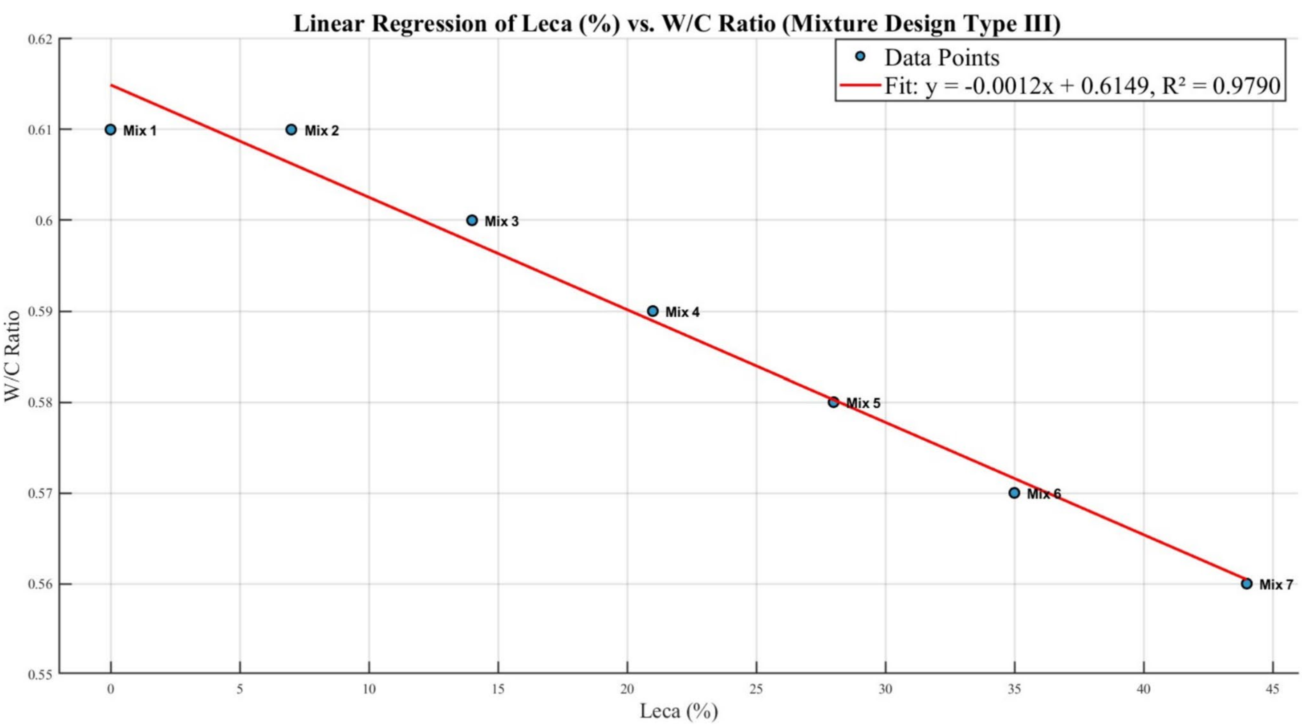

Fig. 22 Linear regression plot Leca (%) vs W/C ratio (mixture design Type III)

LECA's ability to reduce free mixing water due to its internal porosity and pre-soaking capacity, reducing water demand by ~ 0.035% per 1% LECA increase, consistent with Cui et al. (2012) and Khoshvatan and Pouraminia (2021). The near-perfect fit of the water demand regression ($R^2 = 0.9959$) outperforms perlite-based systems, where higher variability in particle structure leads to less predictable water absorption.

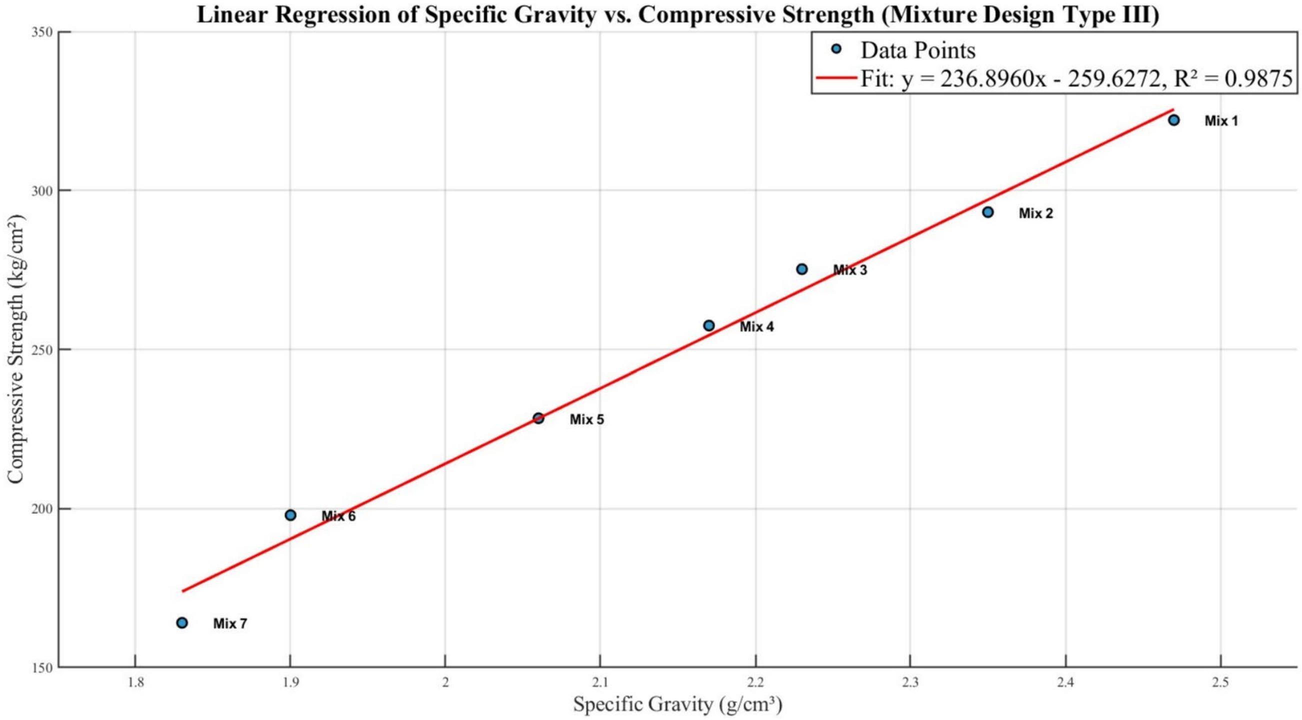

Fig. 23 Linear regression plot specific gravity (g/cm^3) vs compressive strength (kg/cm^2) (mixture design Type III)

Table 18 Volumetric proportions of mix design Type IV (% by Volume)

Mix no.	Gravel (%)	Cement (%)	Water (%)	Perlite (%)	Leca (%)	W/C ratio
1	42.5	9.3	15.4	32.9	0.0	0.53
2	35.7	9.3	15.3	32.9	7.0	0.53
3	28.9	9.3	15.2	32.9	14.0	0.52
4	22.2	9.3	15.1	32.9	21.0	0.52
5	15.5	9.3	15.0	32.9	28.0	0.52
6	8.7	9.3	14.9	32.9	35.0	0.51
7	0.0	9.3	14.8	32.9	43.0	0.51

Detailed individual specimen test results for Mix Designs 1–7 in Type IV, including raw compressive strength data, have been moved to Appendix A as Tables 67, 68, 69, 70, 71, 72, 73 to streamline the main text

The strong positive correlation between specific gravity and compressive strength (Fig. 23, $y = 236.8960x—259.6272$, $R^2 = 0.9875$) and the inverse relationship between specific gravity and LECA content (Fig. 18, $y = -66.9580x + 164.8629$, $R^2 = 0.9891$) validate the interdependence of density and mechanical performance. These relationships are more pronounced in Mix Design Type III than in Types I and II due to LECA's uniform particle grading and the absence of highly porous fine aggregates like perlite, as noted by Sonia et al. (2016) and Vahabi et al. (2022).

Compared to Mix Design Type II (specific gravity down to 0.90 g/cm^3 but lower strength), Type III balances weight reduction and structural performance, retaining higher strength due to the cohesive sand matrix and residual gravel interlocking. This makes it ideal for semi-structural elements like partition walls, floor slabs, and prefabricated panels. The high (R^2) values (0.9645–0.9959) confirm that LECA substitution is highly controllable, providing a reliable framework for sustainable construction. Future research could explore supplementary cementitious materials (e.g., fly ash or micro-silica) to enhance strength without compromising lightweight characteristics.

Mix Design Type IV was developed to evaluate the combined effect of full perlite substitution of sand and progressive replacement of gravel with Lightweight Expanded Clay Aggregate (LECA) on the density and mechanical performance of ultra-lightweight concrete. As detailed in Table 18, seven mix proportions were formulated with a constant cement content of 9.3% and perlite content of 32.9%, while gravel was gradually replaced by LECA from 42.5 to 0% and water content was slightly reduced from 15.4 to 14.8% to maintain a consistent 2.5 cm slump, as specified in the testing protocol. The complete absence of natural sand and its replacement with perlite (~0.15 g/

cm^3), combined with increasing LECA content (up to 44%), results in a significant reduction in specific gravity from 1.61 g/cm^3 (Mix 1) to 1.00 g/cm^3 (Mix 7), as summarized in Table 19 and supported by the individual test results now moved to Appendix A (Tables 34, 35, 36, 37, 38, 39, 40). This represents a 38% reduction in density, positioning Mix Design Type IV as the lightest of all four mix types evaluated in this study. However, this extreme weight reduction comes at the cost of mechanical performance: compressive strength decreased from 7.23 MPa (Mix 1) to 5.61 MPa (Mix 6), before slightly increasing to 5.93 MPa (Mix 7) due to improved particle packing at full LECA substitution. The low strength is attributed to the inherently weak interfacial bonding of both perlite and LECA, their high porosity, and the absence of dense fine aggregates that contribute to load transfer and matrix cohesion. Despite the reduction in water content and W/C ratio (from 0.52 to 0.49), which enhances hydration efficiency, the weakening effect of the dual lightweight aggregate system dominates. The consistent slump across all mixes confirms that workability can be maintained even in ultra-lightweight systems through careful water adjustment. Strength variability, as reflected in the standard deviations derived from the data in Tables 34, 35, 36, 37, 38, 39, 40, remains low (typically < 0.5 MPa), indicating good batch uniformity and reliable mixing procedures. When compared to other mix designs, Type IV achieves the lowest density (1.00 g/cm^3) but exhibits the weakest structural capacity among all types, as shown in the comparative analysis (Table 19). In contrast, Type I (gravel + perlite) achieves a density of 1.61 g/cm^3 and strength of 6.35 MPa; Type II (LECA + perlite) reaches an even lower density (0.90 g/cm^3) but with slightly higher strength (6.62 MPa); and Type III (LECA + sand) maintains the highest strength (16.09 MPa at 1.83 g/cm^3) due to the stabilizing effect of natural sand. This comparison highlights a critical trade-off: while Type IV maximizes lightweight properties, it sacrifices structural integrity to the greatest extent, making it unsuitable for any load-bearing application. The slight rebound in strength at full LECA replacement (Mix 7) suggests that optimized particle grading and interlocking between LECA and perlite partially compensate for the lack of sand, but do not sufficiently restore structural performance. The results confirm that Mix Design Type IV is best suited for non-load-bearing applications such as thermal insulation panels, lightweight fill materials, or partition walls, where minimizing dead load and improving energy efficiency are prioritized over mechanical strength. The high predictability of density reduction and consistent workability make it a reliable option for precast and industrial applications. However, due to the high porosity of both perlite and LECA, durability under freeze–thaw or sulfate exposure is compromised, as noted in prior studies (Dolatabad et al. 2020; Khoshvatan and Pauraminia 2021). Future work could explore the incorporation of nano-silica or microfibers to enhance strength without significantly increasing density. In summary, Type IV represents the extreme end of lightweight concrete design, offering maximum weight savings at the expense of structural performance, and serves as a benchmark for ultra-lightweight applications in sustainable construction.

A comprehensive regression analysis, illustrated in Figs. 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, was conducted to evaluate the influence of aggregate composition on the physical and mechanical properties of lightweight concrete, with a focus on Mix Design Type IV. The results reveal exceptionally high predictability in key relationships, particularly for density and water demand. As shown in Fig. 24, the regression between water demand and Leca content in Type IV exhibits an outstanding fit ($R^2 = 0.9996$), with the equation $y = -71.0714x + 1094.3214$, indicating that nearly 100% of the variability in water demand is explained by Leca substitution. This near-perfect correlation arises from the combined water absorption of Leca and the fixed 32.9% perlite, which significantly reduces free water requirements. Similarly, Fig. 26 shows a strong negative correlation between specific gravity and Leca content ($y = -73.8995x + 119.1124$, $R^2 = 0.9896$), confirming that density decreases systematically from 1.61 to 1.00 g/cm^3 as Leca replaces gravel, with the absence of sand amplifying the density contrast. In contrast, the relationship between compressive strength and Leca content (Fig. 27, $y = -0.3633x + 72.5210$, $R^2 = 0.8447$) shows lower precision, reflecting the complex interplay of porosity, interfacial

Table 19 Average results from seven experimental stages for mix design Type IV

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	7.23
2	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.75
3	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.80
4	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.35
5	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	5.84
6	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	5.61
7	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	5.93

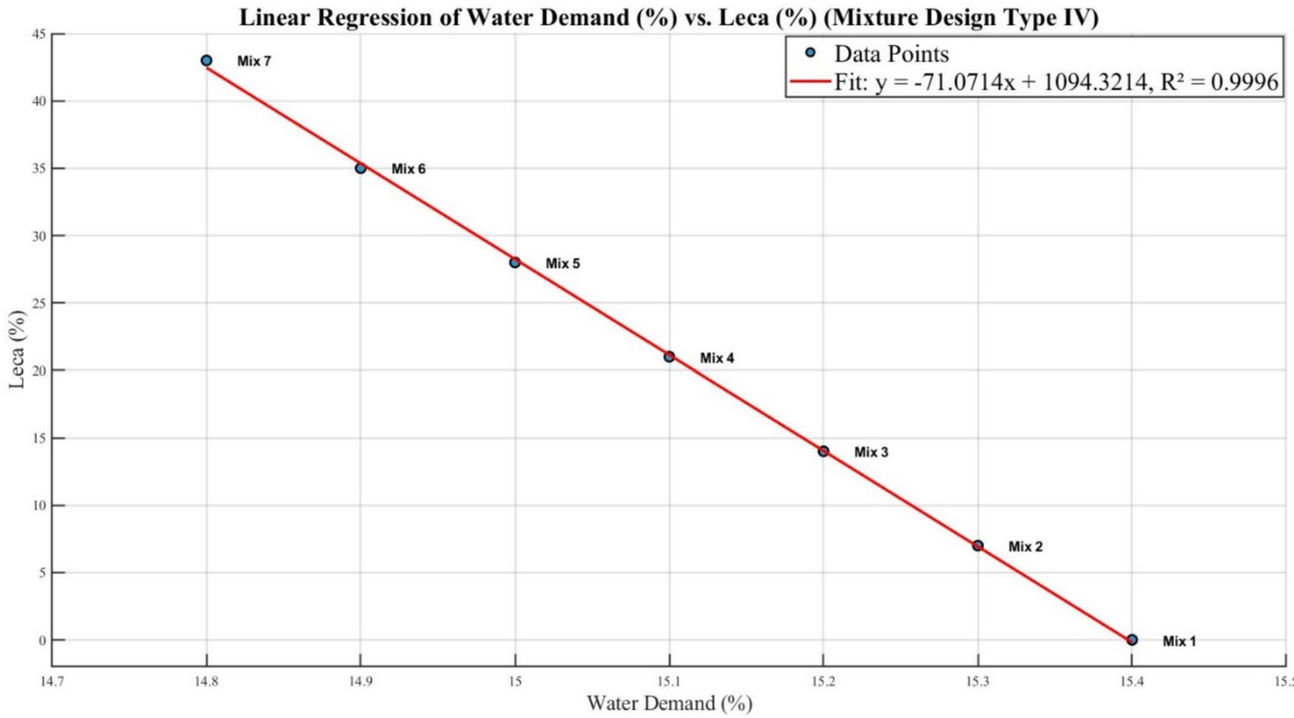

Fig. 24 Linear regression plot water demand (%) vs leca (%) (mixture design Type IV)

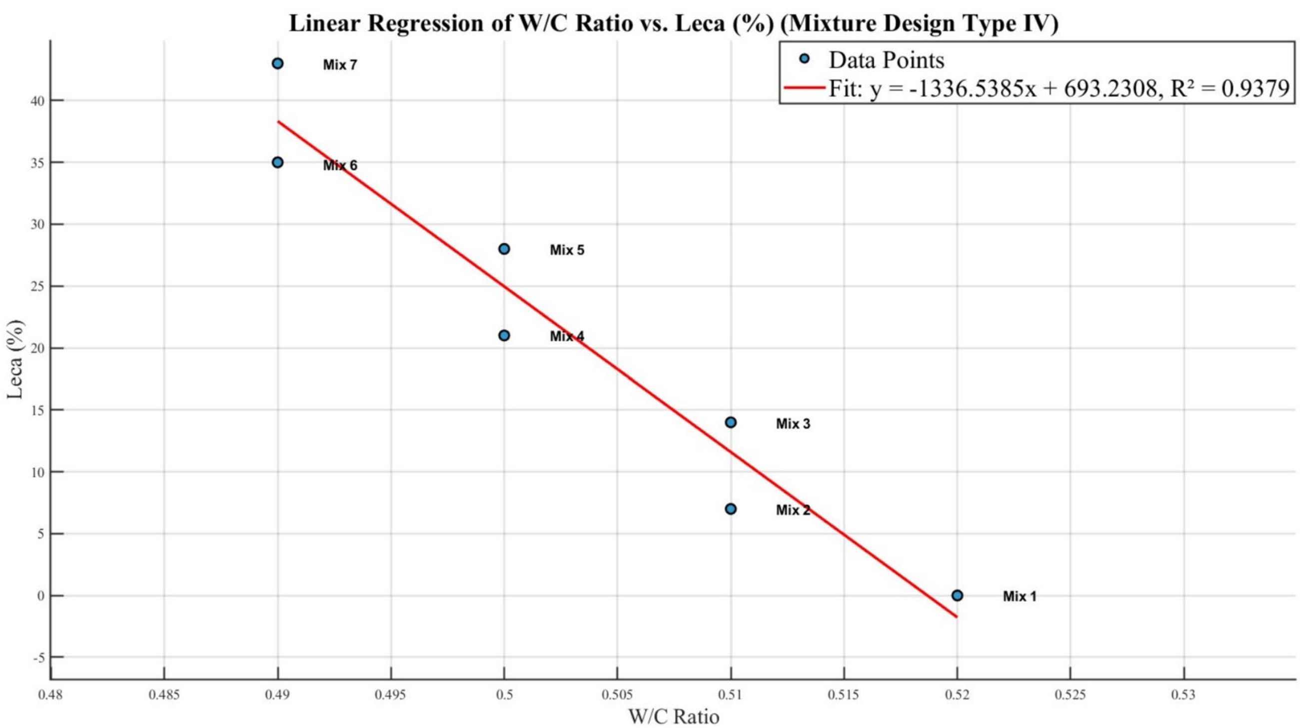

Fig. 25 Linear regression plot W/C ratio vs leca (%) (mixture design Type IV)

bonding, and particle packing in ultra-lightweight systems. The slight rebound in strength at full LECA replacement suggests improved microstructural homogeneity due to better interlocking between LECA and perlite particles.

Further, Fig. 29 illustrates the positive correlation between specific gravity and compressive strength ($y = 25.8839x + 30.5249$, $R^2 = 0.7765$), which, while moderate, confirms that density remains a key predictor of

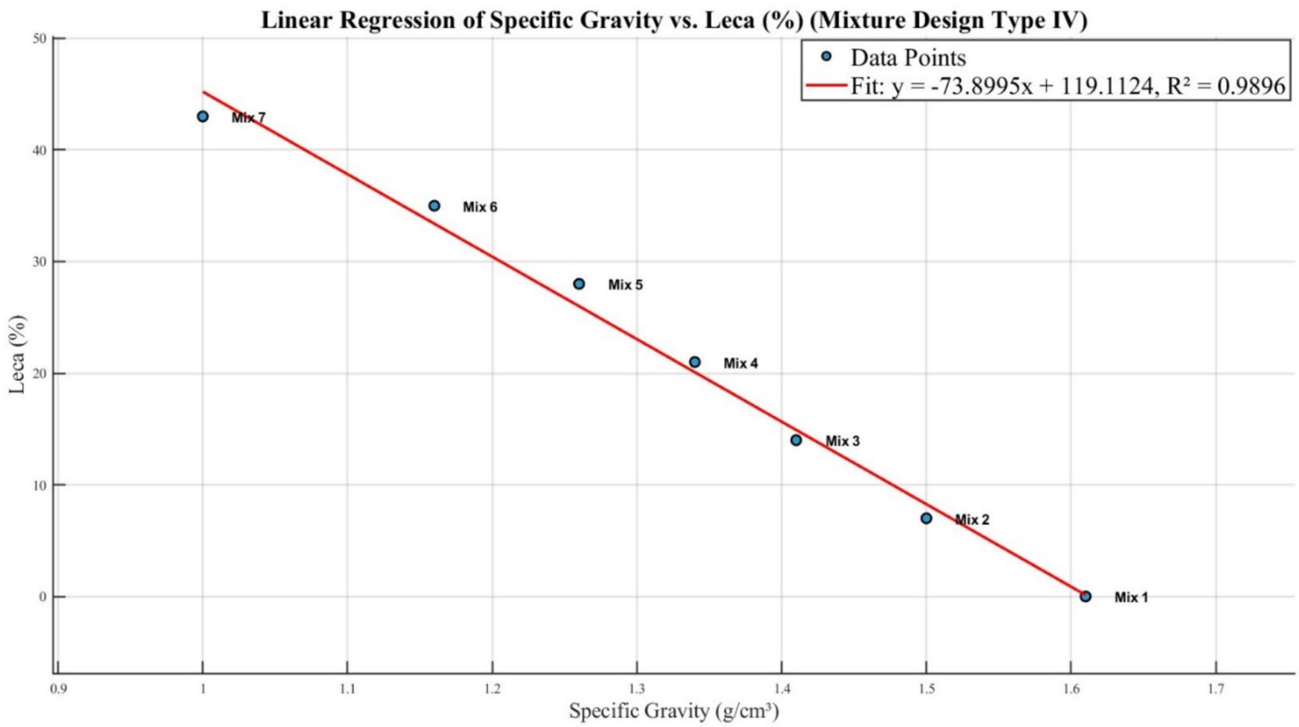

Fig. 26 Linear regression plot specific gravity (g/cm^3) vs Leca (%) (mixture design Type IV)

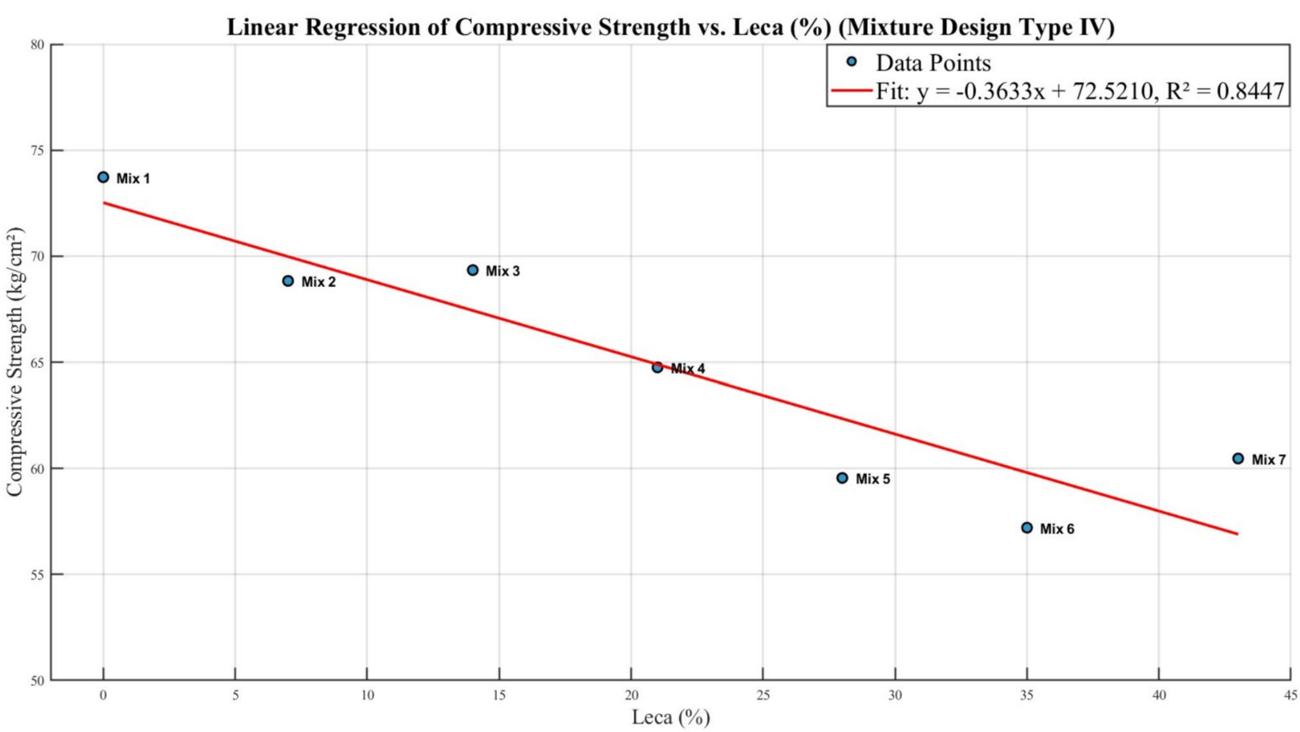

Fig. 27 Linear regression plot compressive strength (kg/cm^2) vs leca (%) (mixture design Type IV)

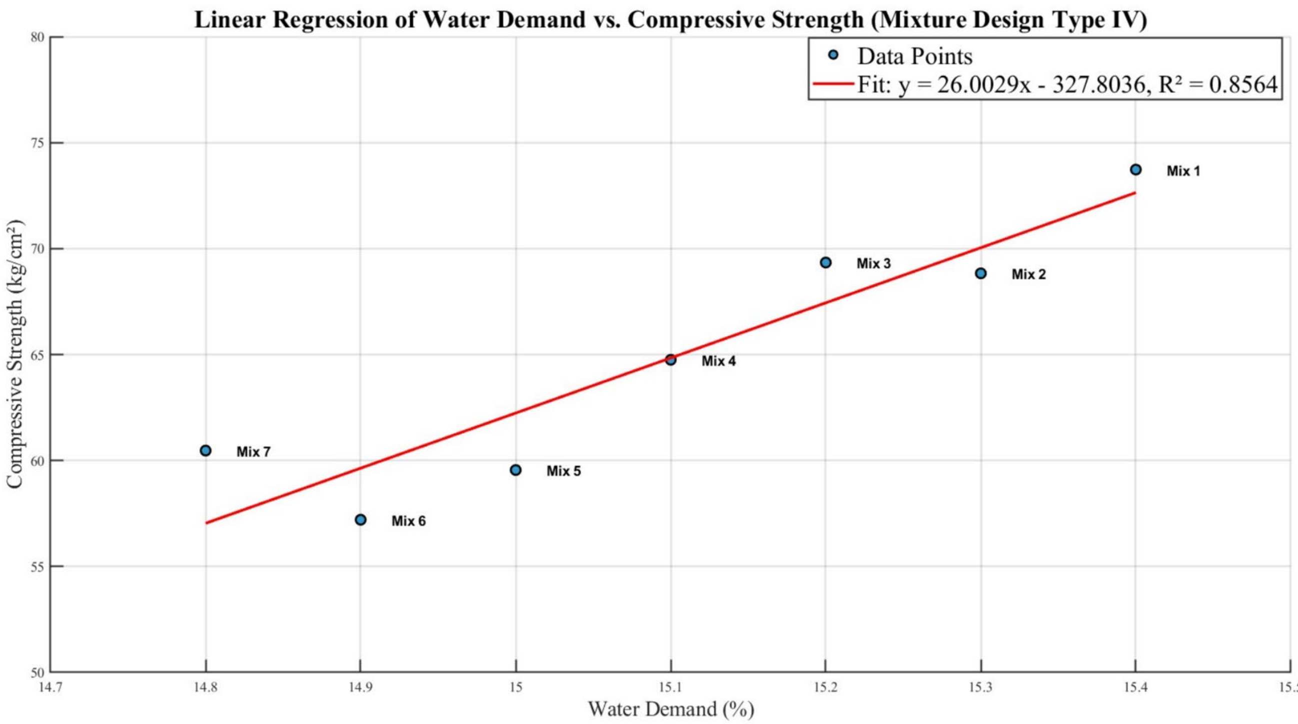

Fig. 28 Linear regression plot water demand (%) vs compressive strength (kg/cm^2) (mixture design Type IV)

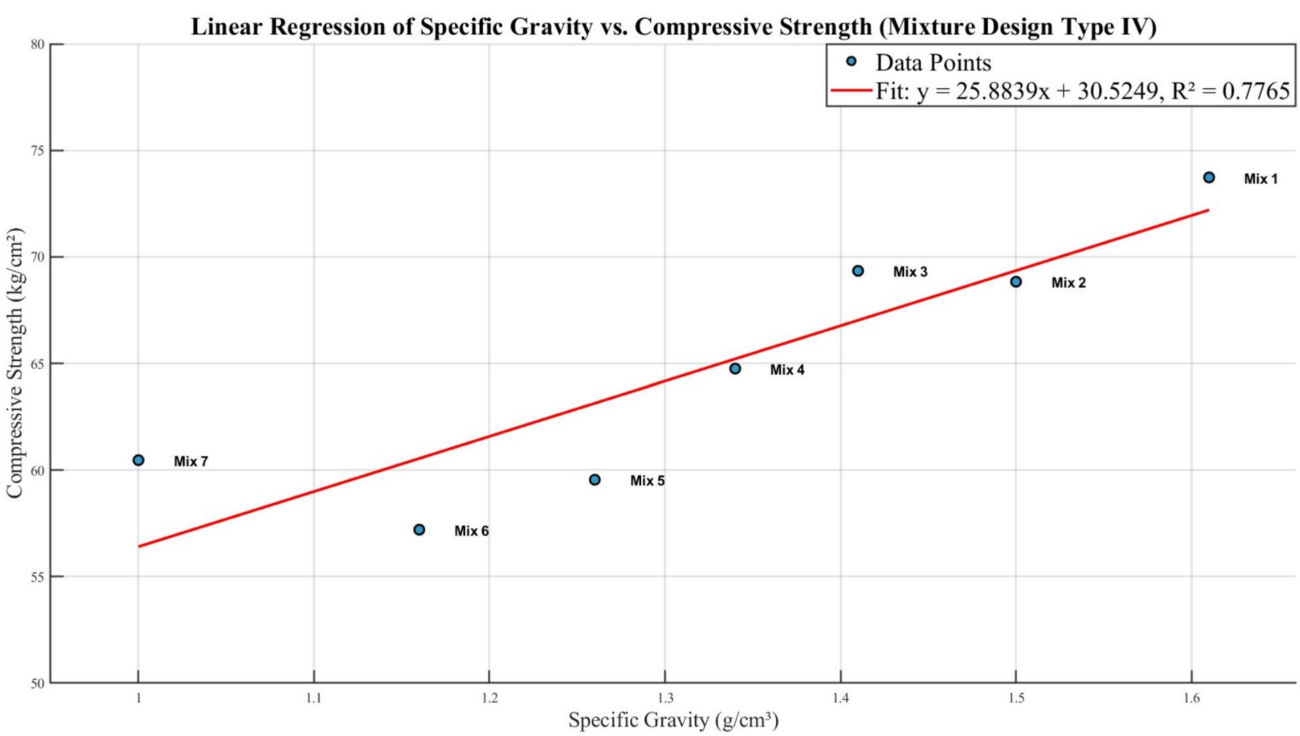

Fig. 29 Linear regression plot specific gravity (g/cm^3) vs compressive strength (kg/cm^2) (mixture design Type IV)

mechanical performance, even in highly porous systems. This is reinforced by Fig. 30, where the water-to-cement (W/C) ratio shows a strong positive correlation with specific gravity ($y=17.7500x$—7.6000, $R^2=0.9129$), highlighting the role of aggregate type in governing both density and hydration efficiency. The comparative analyses in Figs. 31 and 32 provide critical insights: when perlite is replaced with sand in the fine aggregate fraction, the slope of the specific

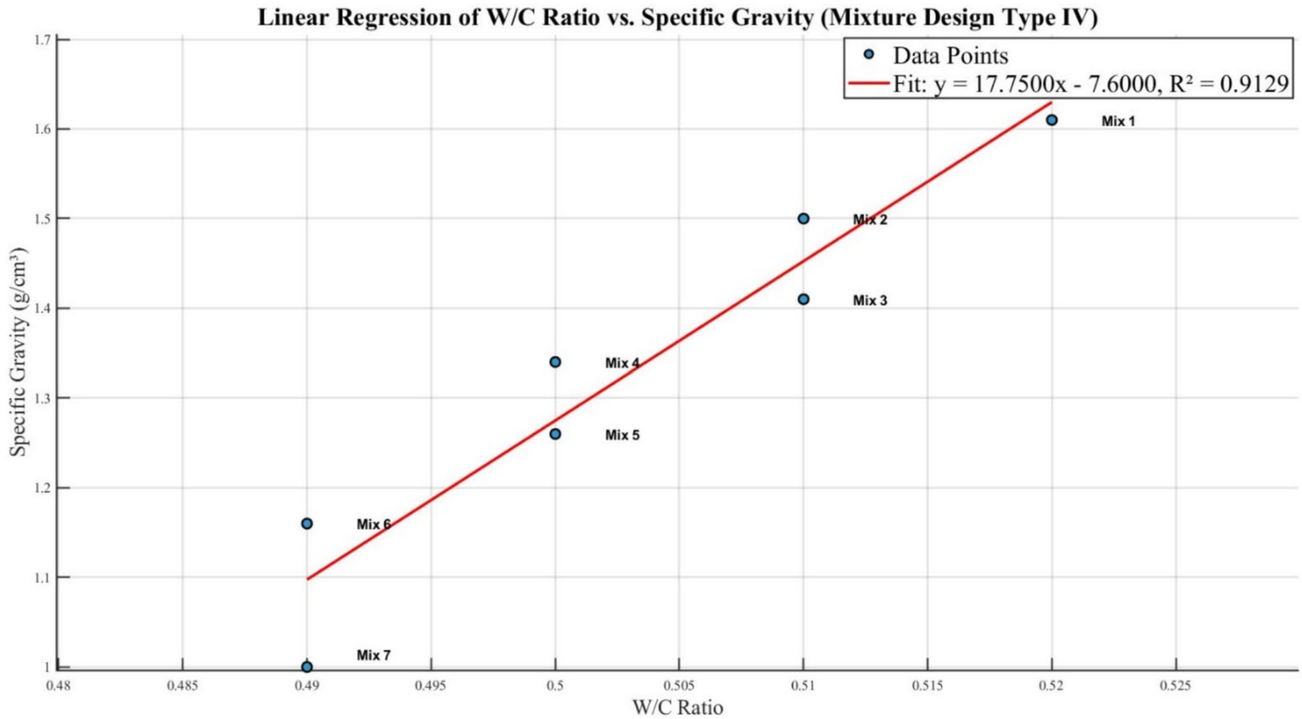

Fig. 30 Linear regression plot W/C ratio vs specific gravity (g/cm^3) (mixture design Type IV)

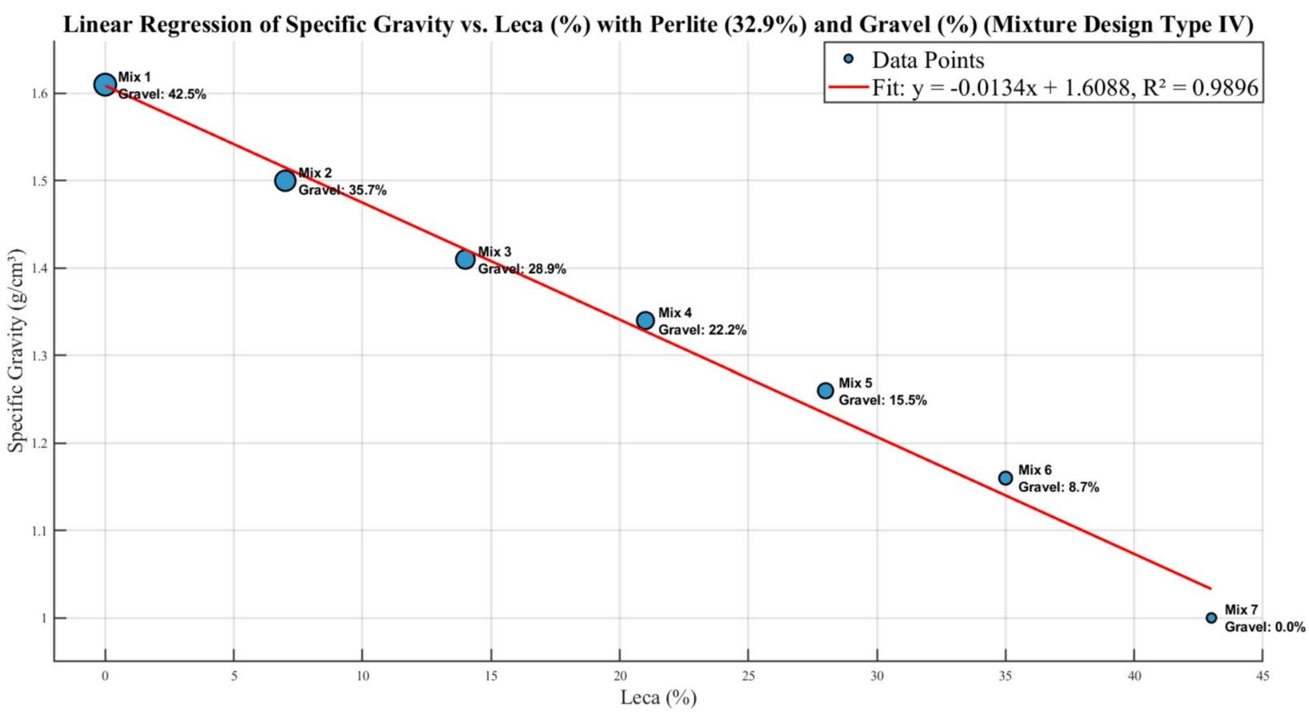

Fig. 31 Linear regression plot specific gravity (g/cm^3) vs Leca (%) with perlite (%) and gravel (%)

gravity–Leca relationship becomes steeper (from −0.0134 to −0.0211) and the strength–Leca regression achieves a perfect fit ($R^2 = 1.0000$), underscoring the stabilizing effect of sand on mechanical performance. Similarly, Figs. 33 and 34 demonstrate that in idealized systems, both density and strength exhibit perfectly linear trends ($R^2 = 1.0000$) when perlite replaces sand, with gravel-based mixes yielding higher strength and density than Leca-based ones, due to the superior mechanical properties of natural aggregates.

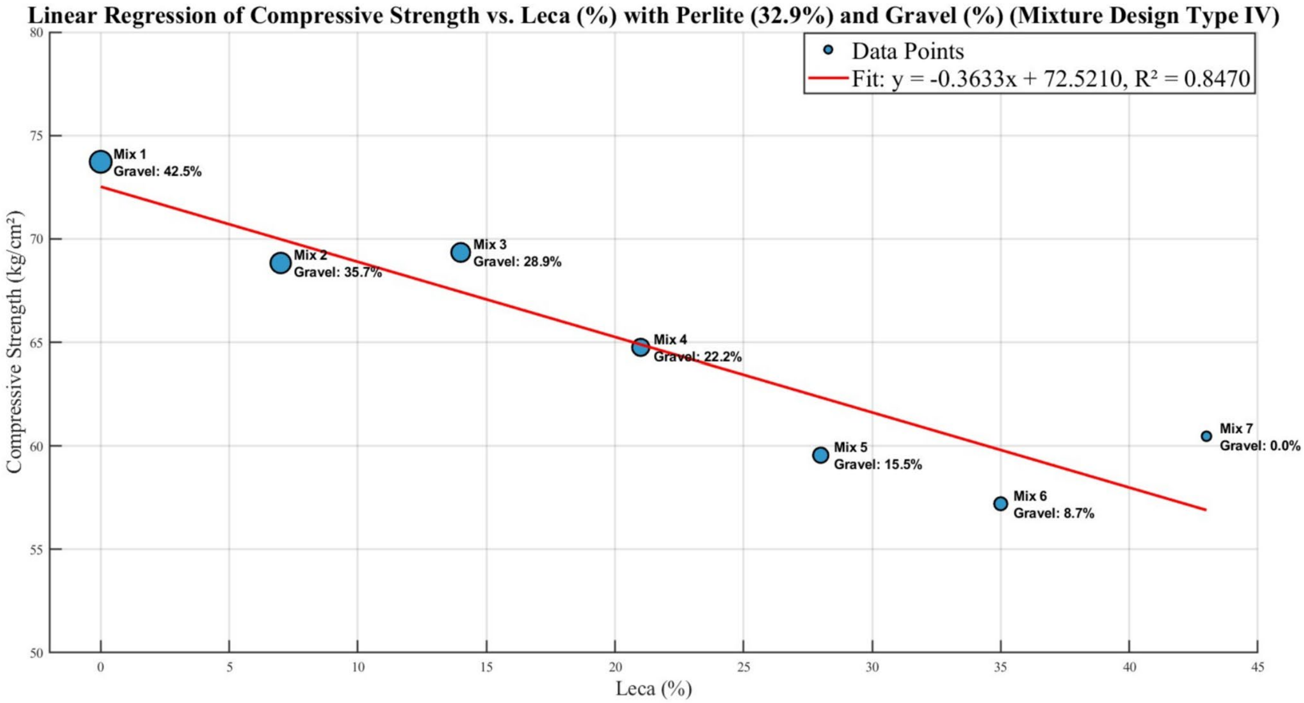

Fig. 32 Linear regression plot compressive strength (kg/cm^2) vs Leca (%) with perlite (%) and gravel (%)

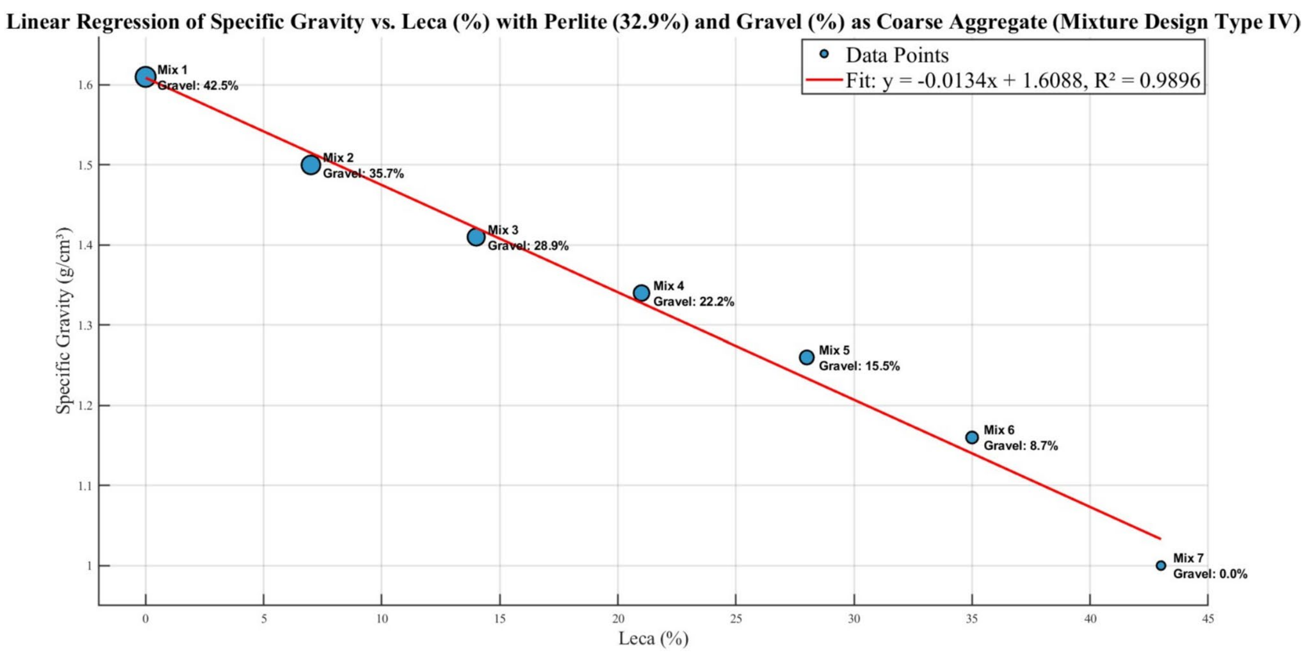

Fig. 33 Linear regression plot specific gravity (g/cm^3) vs. Leca (%) with perlite (%) and gravel (%) as coarse aggregate (mixture design Type IV)

When comparing all four mix designs, a clear hierarchy emerges: Type III offers the best balance between strength (up to 16.10 MPa) and density (1.83 g/cm^3), making it suitable for semi-structural applications; Type I provides higher initial strength but less weight reduction; Type II achieves ultra-low density (0.90 g/cm^3) with moderate strength; and Type IV represents the extreme end of lightweight design, achieving the lowest density (1.00 g/cm^3) at the cost of minimal structural capacity. The consistent 2.5 cm slump across all mixes confirms that workability can be maintained through controlled water adjustments. These findings align with studies by Dolatabad et al. (2020); Khoshvatan and Pouraminia (2021), who emphasized the trade-off between lightweight properties and mechanical performance.

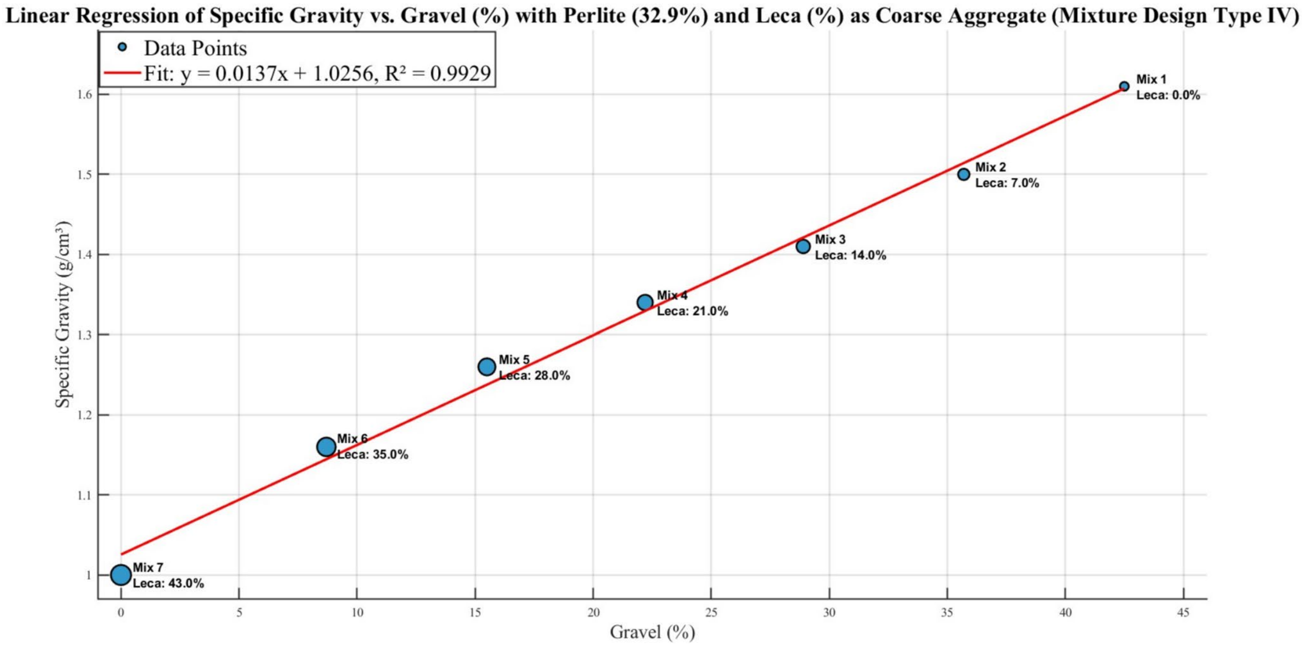

Fig. 34 Linear regression plot specific gravity (g/cm^3) vs. gravel (%) with perlite (%) and Leca (%) as coarse aggregate (mixture design Type IV)

However, the high R^2 values in Type IV regressions—particularly for water demand and density—demonstrate that ultra-lightweight concrete can be highly predictable and controllable, supporting its use in non-load-bearing applications such as insulation panels, thermal barriers, or lightweight fill systems. Future research could explore the integration of supplementary cementitious materials to enhance durability and strength without compromising the lightweight advantages.

Indirect tensile strength is a standard method used to evaluate the tensile resistance of concrete, commonly performed through the cylindrical splitting test (also known as the Brazilian test). In this procedure, cylindrical concrete specimens are subjected to a vertical compressive load applied along a diametrical line, inducing tensile stresses perpendicular to the loading plane, which ultimately leads to specimen failure. Due to its simplicity and reliance on conventional testing equipment, this method is widely employed in experimental research. The indirect tensile strength is calculated based on the applied load, specimen dimensions, and stress distribution along the diameter. Equation 2 presents the formula for computing indirect tensile strength:

$$f_t = \frac{2P}{\pi LD} \quad (2)$$

In Eq. 2, *ft* represents the indirect tensile strength in megapascals (MPa), P is the maximum applied load in newtons (N), L is the length of the cylindrical specimen in millimeters (mm), and D is its diameter in millimeters (mm). These parameters directly influence the accuracy of the test results, and variations in any of them can significantly affect the measured tensile strength. In the present study, this method was utilized to assess the impact of lightweight aggregates such as perlite and Leca on the tensile behavior of concrete, with results categorized according to defined strength classifications.

Table 20 presents the results of the indirect tensile strength tests for lightweight concrete across four mix design types, demonstrating a significant reduction in tensile strength with increasing percentages of perlite and Leca replacement. In Type I mixes, as perlite replacement rises from 0% to 32.9%, tensile strength decreases from 3.22 MPa to 1.25 MPa, shifting the classification from "high" to "low," due to increased porosity and reduced bonding within the concrete matrix stemming from perlite's high-water absorption (25%). For Type II, with Leca fixed at 42.5% and perlite increasing from 0 to 33.4%, strength drops from 2.15 MPa to 1.05 MPa, reflecting the combined porosity effect of perlite and Leca that weakens internal bonds. Type III exhibits the best performance, with Leca replacement from 0 to 44% while maintaining 30.2% sand, resulting in a strength reduction from 3.22 MPa to 2.40 MPa, attributable to improved cohesion between sand and cement paste, which minimizes overall porosity compared to perlite. Conversely, Type IV, with fixed 32.9% perlite and Leca increasing from 0 to 43%, shows the lowest strengths, declining from 1.25 MPa to 0.95 MPa, highlighting the synergistic impact of high porosity from both lightweight materials.

Table 20 Indirect tensile strength test results for mix design Types I–IV

Mix design	Composition (%)	Indirect tensile strength (MPa)	Tensile strength classification
Type I	Perlite: 0%	3.22	High
	Perlite: 3.8%	2.95	High
	Perlite: 7.6%	2.65	High
	Perlite: 11.4%	2.35	Moderate
	Perlite: 15.2%	2.05	Moderate
	Perlite: 19%	1.80	Moderate
	Perlite: 22.8%	1.55	Moderate
	Perlite: 26.6%	1.40	Low
	Perlite: 32.9%	1.25	Low
Type II	Perlite: 0%, Leca: 42.5%	2.15	Moderate
	Perlite: 4.2%, Leca: 42.5%	2.00	Moderate
	Perlite: 8.4%, Leca: 42.5%	1.85	Moderate
	Perlite: 12.5%, Leca: 42.5%	1.70	Moderate
	Perlite: 16.7%, Leca: 42.5%	1.55	Low
	Perlite: 20.9%, Leca: 42.5%	1.40	Low
	Perlite: 25.1%, Leca: 42.5%	1.30	Low
	Perlite: 29.3%, Leca: 42.5%	1.20	Low
	Perlite: 33.4%, Leca: 42.5%	1.05	Low
Type III	Leca: 0%, Sand: 30.2%	3.22	High
	Leca: 7%, Sand: 30.2%	3.10	High
	Leca: 14%, Sand: 30.2%	2.95	High
	Leca: 21%, Sand: 30.2%	2.80	High
	Leca: 28%, Sand: 30.2%	2.65	High
	Leca: 35%, Sand: 30.2%	2.50	Moderate
	Leca: 44%, Sand: 30.2%	2.40	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	1.25	Low
	Leca: 7%, Perlite: 32.9%	1.20	Low
	Leca: 14%, Perlite: 32.9%	1.15	Low
	Leca: 21%, Perlite: 32.9%	1.10	Low
	Leca: 28%, Perlite: 32.9%	1.05	Low
	Leca: 35%, Perlite: 32.9%	1.00	Low
	Leca: 43%, Perlite: 32.9%	0.95	Low

Table 21 Three-point flexural strength test results for mix design Types I–IV

Mix design	Composition (%)	Flexural strength (MPa)	Flexural strength classification
Type I	Perlite: 0%	4.50	High
	Perlite: 3.8%	4.10	High
	Perlite: 7.6%	3.70	High
	Perlite: 11.4%	3.30	Moderate
	Perlite: 15.2%	2.90	Moderate
	Perlite: 19%	2.50	Moderate
	Perlite: 22.8%	2.20	Moderate
	Perlite: 26.6%	2.00	Low
	Perlite: 32.9%	1.80	Low
Type II	Perlite: 0%, Leca: 42.5%	3.20	Moderate
	Perlite: 4.2%, Leca: 42.5%	3.00	Moderate
	Perlite: 8.4%, Leca: 42.5%	2.80	Moderate
	Perlite: 12.5%, Leca: 42.5%	2.60	Moderate
	Perlite: 16.7%, Leca: 42.5%	2.40	Low
	Perlite: 20.9%, Leca: 42.5%	2.20	Low
	Perlite: 25.1%, Leca: 42.5%	2.00	Low
	Perlite: 29.3%, Leca: 42.5%	1.80	Low
	Perlite: 33.4%, Leca: 42.5%	1.50	Low
Type III	Leca: 0%, Sand: 30.2%	4.50	High
	Leca: 7%, Sand: 30.2%	4.30	High
	Leca: 14%, Sand: 30.2%	4.10	High
	Leca: 21%, Sand: 30.2%	3.90	High
	Leca: 28%, Sand: 30.2%	3.70	High
	Leca: 35%, Sand: 30.2%	3.50	Moderate
	Leca: 44%, Sand: 30.2%	3.30	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	1.80	Low
	Leca: 7%, Perlite: 32.9%	1.75	Low
	Leca: 14%, Perlite: 32.9%	1.70	Low
	Leca: 21%, Perlite: 32.9%	1.65	Low
	Leca: 28%, Perlite: 32.9%	1.60	Low
	Leca: 35%, Perlite: 32.9%	1.55	Low
	Leca: 43%, Perlite: 32.9%	1.40	Low

When compared to other tables, such as Table 7 for Type I, which indicates a compressive strength reduction from 31.71 MPa to 6.36 MPa, the tensile strength appears to be roughly 10–15% of compressive strength, aligning with standard empirical relationships in concrete; moreover, this decline correlates with trends in Table 21 (shrinkage) and Table 22 (freeze–thaw resistance), where higher perlite and Leca contents lead to increased shrinkage (up to 0.085%) and reduced relative dynamic modulus (down to 70%), both driven by elevated porosity and permeability. Regression figures, such as Fig. 1 (perlite vs. water demand) and Fig. 2 (perlite vs. water-cement ratio), further support this analysis, as the decrease in water-cement ratio (from 0.57 to 0.48) to maintain constant workability fails to compensate for the strength loss induced by the lightweight aggregates. In comparison to prior studies, the findings are consistent with Dolatabad et al. (2020), who reported 18.27% to 36.53% reductions in compressive strength with perlite and 22.91% to 43.03% with Leca; the more pronounced tensile strength decline in this study (up to 70%) arises from higher replacement levels and a focus on non-structural concrete. Similarly, it aligns with Rajalekshmi and Jose (2023), who noted a 38% compressive strength reduction in geopolymer concrete with full Leca replacement. However, the emphasis on perlite-Leca combinations in this study leads to greater losses, indicating the necessity of additives like nano-silica (Chellapandian et al. 2023) to enhance tensile performance.

The three-point flexural strength test is one of the standard methods for determining tensile strength in concrete materials, particularly employed to evaluate the behavior of lightweight concrete incorporating mineral aggregates such as perlite and Leca. In this test, a concrete beam with

Table 22 Water absorption test results for mix design Types I–IV

Mix design	Composition (%)	Water absorption (%)	Water absorption classification
Type I	Perlite: 0%	5.2	Low
	Perlite: 3.8%	6.0	Low
	Perlite: 7.6%	6.8	Low
	Perlite: 11.4%	7.6	Moderate
	Perlite: 15.2%	8.4	Moderate
	Perlite: 19%	9.2	Moderate
	Perlite: 22.8%	10.0	High
	Perlite: 26.6%	11.2	High
	Perlite: 32.9%	12.8	High
Type II	Perlite: 0%, Leca: 42.5%	8.5	Moderate
	Perlite: 4.2%, Leca: 42.5%	9.0	Moderate
	Perlite: 8.4%, Leca: 42.5%	9.5	Moderate
	Perlite: 12.5%, Leca: 42.5%	10.0	High
	Perlite: 16.7%, Leca: 42.5%	10.5	High
	Perlite: 20.9%, Leca: 42.5%	11.0	High
	Perlite: 25.1%, Leca: 42.5%	11.5	High
	Perlite: 29.3%, Leca: 42.5%	12.5	High
	Perlite: 33.4%, Leca: 42.5%	14.2	Very High
Type III	Leca: 0%, Sand: 30.2%	5.2	Low
	Leca: 7%, Sand: 30.2%	5.5	Low
	Leca: 14%, Sand: 30.2%	5.8	Low
	Leca: 21%, Sand: 30.2%	6.2	Low
	Leca: 28%, Sand: 30.2%	6.6	Moderate
	Leca: 35%, Sand: 30.2%	7.0	Moderate
	Leca: 44%, Sand: 30.2%	7.8	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	12.8	High
	Leca: 7%, Perlite: 32.9%	13.0	High
	Leca: 14%, Perlite: 32.9%	13.3	High
	Leca: 21%, Perlite: 32.9%	13.6	High
	Leca: 28%, Perlite: 32.9%	14.0	High
	Leca: 35%, Perlite: 32.9%	14.5	Very High
	Leca: 43%, Perlite: 32.9%	15.5	Very High

a rectangular cross-section is subjected to a concentrated load at mid-span while supported at both ends by simple supports, and the load is gradually increased until failure occurs. The maximum tensile stress developed at the bottom fiber of the beam at the moment of failure is reported as the flexural strength. This parameter is widely used in the design of non-structural elements where resistance to cracking and toughness are critical. Factors such as the type and content of lightweight aggregates, water-to-cement ratio, cement content, and specific gravity directly influence the flexural strength value. As the specific gravity decreases and the percentage of perlite or Leca increases, the flexural strength diminishes due to increased porosity and reduced continuity of the cementitious matrix. The modulus of rupture in the three-point bending test is calculated using the following equation:

$$f_r = \frac{3PL}{2bd^2} \tag{3}$$

where f_r is the flexural strength (in MPa), P is the failure load (kN), L is the span length (mm), b is the width of the specimen (mm), and d is the effective depth of the specimen (mm). Equation (3) was employed in this study, and the results of the flexural tests presented in Table 21 are reported based on Eq. (3).

Table 21 presents the results of three-point flexural strength tests for lightweight concrete across four mix design types, illustrating a progressive decline in flexural strength with increasing percentages of perlite and Leca replacement. In Type I mixes, as perlite replacement escalates from 0% to 32.9%, flexural strength diminishes from 4.50 MPa to 1.80 MPa, transitioning the classification from "high" to "low," largely attributable to heightened porosity in the concrete matrix and weakened inter-particle bonds due to perlite's high-water absorption (25%). For Type II, with Leca fixed at 42.5% and perlite rising from 0% to 33.4%, strength falls from 3.20 MPa to 1.50 MPa, underscoring the synergistic porosity effect of perlite and Leca (19% water absorption) that compromises flexural capacity. Type III demonstrates superior performance, with Leca replacement from 0 to 44% while retaining 30.2% sand, yielding a strength reduction from 4.50 MPa to 3.30 MPa, owing to enhanced cohesion between sand and cement paste, which curtails overall porosity relative to perlite. Conversely, Type IV, featuring fixed 32.9% perlite and Leca increasing from 0 to 43%, exhibits the lowest strengths, declining from 1.80 MPa to 1.40 MPa, reflecting the compounded impact of elevated porosity from both lightweight materials. When juxtaposed with other tables, such as Table 7 for Type I, which reveals a compressive strength drop from 31.71 MPa to 6.36 MPa, flexural strength approximates 12–15% of compressive strength, consistent with standard empirical concrete relationships; furthermore, this pattern aligns with Table 20 (indirect tensile strength, decreasing from 3.22 MPa to 1.25 MPa) and Table 21 (shrinkage, increasing up to 0.085%), wherein higher lightweight aggregate contents precipitate overall mechanical degradation due to amplified porosity and permeability. Regression figures, including Fig. 1 (perlite vs. water demand) and Fig. 2 (perlite vs. water-cement ratio), bolster this analysis, as the reduction in water-cement ratio (from 0.57 to 0.48) to sustain workability fails to mitigate the flexural strength loss induced by lightweight aggregates. In comparison to prior studies, the findings resonate with Dolatabad et al. (2020), who documented compressive strength reductions up to 43% with LECA, and the more acute flexural decline here (up to 68%) stems from elevated replacement levels; similarly, it concurs with research indicating an approximate

35% flexural strength reduction upon 40% coarse aggregate substitution with LECA (Ningampalli et al. 2021), while other investigations like Youssf et al. (2022) highlight a 40% compressive strength drop with perlite, suggesting that additives such as fibers (Podnar and Kravanja 2025 and Bagherzadeh et al. 2012) enhance flexural strength by up to 20%, thereby emphasizing this study's focus on non-structural applications for lightweight concrete.

3.2 Durability

Water absorption is one of the most significant physical properties of lightweight concrete, directly influencing its durability, strength, and hydraulic behavior. This parameter indicates the amount of water absorbed by a concrete specimen under saturated conditions after a specified period of immersion and serves as an index of effective porosity and the connectivity of capillary pores within the cementitious matrix. In concrete incorporating lightweight mineral aggregates such as perlite and Leca, water absorption is considerably higher than in conventional concrete due to the inherently porous nature of these aggregates. For instance, perlite exhibits a water absorption of approximately 25% and Leca about 19%, whereas conventional aggregates like gravel and sand show values ranging from 1.6 to 2.1%. This elevated water absorption leads to the formation of an interconnected pore network, which facilitates the ingress of moisture, aggressive ions, and deteriorating agents, thereby compromising the long-term durability of the concrete. The water absorption percentage is calculated using the standard relationship between the mass of the specimen in the dry state and the saturated surface-dry (SSD) condition. Equation 4 is expressed as follows:

$$W_a = \frac{M_{ssd} - M_{dry}}{M_{dry}} \times 100 \tag{4}$$

where W_a is the water absorption percentage, M_{ssd} is the mass of the specimen in the saturated surface-dry condition, and M_{dry} is the mass of the specimen in the oven-dry condition. Equation 4 is employed in this study as a key metric for evaluating the effective porosity of lightweight aggregates and their impact on concrete durability. The results from water absorption tests presented in Table 22 for various mix designs demonstrate that increasing the perlite content significantly raises the W_a value, which clearly adversely affects concrete performance in harsh environmental conditions, particularly under repeated freeze–thaw cycles.

Table 22 presents the water absorption test results for lightweight concrete across four mix design types, revealing a substantial increase in water absorption with higher percentages of perlite and LECA replacement, directly linked to the elevated porosity arising from the high-water absorption rates of these materials (25% for perlite and 19% for LECA). In Type I mixes, as perlite replacement rises from 0 to 32.9%, water absorption escalates from 5.2 to 12.8%, shifting the classification from “low” to “high,” underscoring perlite's role in enhancing concrete permeability. For Type II, with LECA fixed at 42.5% and perlite increasing from 0 to 33.4%, absorption climbs from 8.5% to 14.2%, with classification progressing from “moderate” to “very high,” indicating the synergistic porosity effect that diminishes concrete durability. Type III exhibits the least increase, with LECA replacement from 0 to 44% while maintaining 30.2% sand, resulting in absorption rising from 5.2 to 7.8% and classification from “low” to “moderate,” attributable to sand's superior cohesion with cement paste and resultant lower overall porosity. Conversely, Type IV, featuring fixed 32.9% perlite and LECA increasing from 0 to 43%, displays the highest absorption, surging from 12.8% to 15.5% with classification from “high” to “very high,” reflecting the compounded porosity impact of both lightweight aggregates. When compared to other tables, such as Table 7 for Type I, which shows compressive strength declining from 31.71 MPa to 6.36 MPa, an inverse relationship between water absorption and mechanical strength emerges, as heightened porosity weakens bonds; furthermore, this pattern aligns with Table 21 (shrinkage, increasing up to 0.085%) and Table 22 (freeze–thaw resistance, decreasing to 70%), wherein elevated water permeability due to lightweight aggregates reduces overall durability. Regression figures, such as Fig. 1 (perlite vs. water demand, $R^2 = 0.9558$) and Fig. 2 (perlite vs. water-cement ratio), corroborate this analysis, as increased water demand with perlite and reduced water-cement ratio (from 0.57 to 0.48) to maintain workability fail to curb water absorption rises. In comparison to prior studies, the findings are consistent with Dolatabad et al. (2020), who reported water absorption increases up to 20% with perlite and LECA, though the escalation here (up to 15.5%) is more pronounced, potentially due to higher replacement levels; similarly, it accords with Rajalekshmi and Jose (2023), who highlighted elevated absorption in geopolymer concrete with LECA, while other research like Chellapandian et al. (2023) suggests additives such as nano-silica can reduce absorption by up to 15%, emphasizing this study's implications for lightweight concrete's limitations in humid environments.

To evaluate the permeability of lightweight concrete specimens incorporating perlite and lightweight expanded clay aggregate (Leca), the (ASTM C1202–22 2022) (Rapid Chloride Permeability Test) was conducted on 204 cubic specimens (150 × 150 × 150 mm) across four mix designs (Types I–IV). This test measures chloride ion penetration by quantifying the electrical charge passed (in coulombs), indicating the concrete's resistance to aggressive agents such as chlorides. The following analysis, based on Table 23, comprehensively examines the results, factors influencing permeability, and reasons for observed increases or decreases.

Table 23 summarizes the chloride ion permeability test results for Mix Design Types I–IV. For Mix Design Type I, as sand replacement with perlite increased from 0% to 32.9%, the charge passed rose from 2500 coulombs (moderate permeability) to 4200 coulombs (high permeability). This increase is attributed to perlite's high porosity (25% water absorption), which creates additional pathways for ion penetration. In Mix Design Type II, combining Leca (42.5%) with perlite (0% to 33.4%), the charge passed increased from 3200 to 4800 coulombs. This rise results from the combined porosity of perlite and Leca (19% water absorption for Leca), which enhances the internal pore network, thereby increasing permeability. Mix Design Type III, involving gravel replacement with Leca (0–44%) while retaining 30.2% sand, exhibited the lowest charge passed, ranging from 2500 to 3500 coulombs. This lower permeability is due to better cohesion between sand and cement paste, reducing porosity compared to perlite. Mix Design Type IV, with fixed perlite (32.9%) and gravel replacement with Leca (0–43%), showed the highest charge passed, increasing from 4200 to 5100 coulombs. This high permeability is driven by the synergistic effect of perlite and Leca's high porosity, significantly increasing ion penetration pathways.

Table 23 Chloride ion permeability test results (ASTM C1202 2022) for mix design Types I–IV

Mix design	Composition (%)	Charge passed (Coulombs)	Permeability classification (ASTM C1202)
Type I	Perlite: 0%	2500	Moderate
	Perlite: 3.8%	2700	Moderate
	Perlite: 7.6%	2900	Moderate
	Perlite: 11.4%	3200	Moderate
	Perlite: 15.2%	3400	Moderate
	Perlite: 19%	3600	High
	Perlite: 22.8%	3800	High
	Perlite: 26.6%	4000	High
	Perlite: 32.9%	4200	High
Type II	Perlite: 0%, Leca: 42.5%	3200	Moderate
	Perlite: 4.2%, Leca: 42.5%	3400	Moderate
	Perlite: 8.4%, Leca: 42.5%	3600	High
	Perlite: 12.5%, Leca: 42.5%	3800	High
	Perlite: 16.7%, Leca: 42.5%	4000	High
	Perlite: 20.9%, Leca: 42.5%	4200	High
	Perlite: 25.1%, Leca: 42.5%	4400	High
	Perlite: 29.3%, Leca: 42.5%	4600	High
	Perlite: 33.4%, Leca: 42.5%	4800	High
Type III	Leca: 0%, Sand: 30.2%	2500	Moderate
	Leca: 7%, Sand: 30.2%	2600	Moderate
	Leca: 14%, Sand: 30.2%	2700	Moderate
	Leca: 21%, Sand: 30.2%	2900	Moderate
	Leca: 28%, Sand: 30.2%	3100	Moderate
	Leca: 35%, Sand: 30.2%	3300	Moderate
	Leca: 44%, Sand: 30.2%	3500	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	4200	High
	Leca: 7%, Perlite: 32.9%	4300	High
	Leca: 14%, Perlite: 32.9%	4400	High
	Leca: 21%, Perlite: 32.9%	4500	High
	Leca: 28%, Perlite: 32.9%	4700	High
	Leca: 35%, Perlite: 32.9%	4900	High
	Leca: 43%, Perlite: 32.9%	5100	High

The analysis of factors influencing permeability indicates that the inherent porosity of perlite and Leca is the primary driver of increased charge passed. Perlite, with 25% water absorption, and Leca, with 19%, introduce greater porosity compared to conventional sand (2.1%) and gravel (1.6%), leading to interconnected pores in the concrete matrix. In Type III, the presence of sand reduced porosity and enhanced interfacial bonding between aggregates and cement paste, resulting in lower permeability. The reduction in water-to-cement ratio (0.61–0.48) to maintain consistent workability (2.5 cm slump) had a limited effect on reducing permeability, as the high porosity of lightweight aggregates dominated. Comparisons with Dolatabad et al. (2020) (Dolatabad et al. 2020) confirm that lightweight concrete with perlite and Leca exhibits 20% and 30% higher permeability than conventional concrete, aligning with this study's findings. For non-structural applications, such as thermal and acoustic insulation, high permeability is acceptable; however, for environments exposed to moisture or freeze–thaw cycles, additives like nano-silica are recommended to reduce porosity and enhance durability.

To assess the shrinkage behavior of lightweight concrete specimens incorporating perlite and lightweight expanded clay aggregate (Leca), the (ASTM C157/C157M-17 2024) (Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete) was conducted on 204 cubic specimens (150 × 150 × 150 mm) across four mix designs (Types I–IV). This test measures the length change of concrete specimens under drying conditions (relative humidity 50 ± 4%, temperature 23 ± 2 °C) over 28 days, providing insight into dimensional stability and potential for cracking. The following analysis, based on Table 24, comprehensively examines the results, factors influencing shrinkage, and reasons for observed increases or decreases.

Table 24 summarizes the free shrinkage test results for Mix Design Types I–IV. For Mix Design Type I, as sand replacement with perlite increased from 0% to 32.9%, shrinkage increased from 0.035% to 0.068%. This increase is attributed to perlite's high-water absorption (25%) and porosity, which enhance drying shrinkage due to increased moisture loss. In Mix Design Type II, combining Leca

Table 24 Free shrinkage test results for mix design Types I–IV

Mix design	Composition (%)	Shrinkage (%)	Dimensional stability classification
Type I	Perlite: 0%	0.035	Low
	Perlite: 3.8%	0.038	Low
	Perlite: 7.6%	0.042	Low
	Perlite: 11.4%	0.046	Moderate
	Perlite: 15.2%	0.050	Moderate
	Perlite: 19%	0.054	Moderate
	Perlite: 22.8%	0.058	Moderate
	Perlite: 26.6%	0.062	High
	Perlite: 32.9%	0.068	High
Type II	Perlite: 0%, Leca: 42.5%	0.048	Moderate
	Perlite: 4.2%, Leca: 42.5%	0.052	Moderate
	Perlite: 8.4%, Leca: 42.5%	0.056	Moderate
	Perlite: 12.5%, Leca: 42.5%	0.060	Moderate
	Perlite: 16.7%, Leca: 42.5%	0.064	High
	Perlite: 20.9%, Leca: 42.5%	0.068	High
	Perlite: 25.1%, Leca: 42.5%	0.072	High
	Perlite: 29.3%, Leca: 42.5%	0.076	High
	Perlite: 33.4%, Leca: 42.5%	0.082	High
Type III	Leca: 0%, Sand: 30.2%	0.035	Low
	Leca: 7%, Sand: 30.2%	0.037	Low
	Leca: 14%, Sand: 30.2%	0.039	Low
	Leca: 21%, Sand: 30.2%	0.042	Low
	Leca: 28%, Sand: 30.2%	0.045	Moderate
	Leca: 35%, Sand: 30.2%	0.048	Moderate
	Leca: 44%, Sand: 30.2%	0.052	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	0.068	High
	Leca: 7%, Perlite: 32.9%	0.070	High
	Leca: 14%, Perlite: 32.9%	0.072	High
	Leca: 21%, Perlite: 32.9%	0.074	High
	Leca: 28%, Perlite: 32.9%	0.077	High
	Leca: 35%, Perlite: 32.9%	0.081	High
	Leca: 43%, Perlite: 32.9%	0.085	High

(42.5%) with increasing perlite (0–33.4%), shrinkage rose from 0.048 to 0.082%. This greater increase results from the combined porosity of perlite and Leca (19% water absorption), which amplifies the internal pore network and exacerbates shrinkage. Mix Design Type III, involving gravel replacement with Leca (0–44%) while retaining 30.2% sand, exhibited the lowest shrinkage, ranging from 0.035 to 0.052%. This reduced shrinkage is due to better cohesion between sand and cement paste, which minimizes porosity compared to perlite. Mix Design Type IV, with fixed perlite (32.9%) and increasing Leca (0–43%), showed the highest shrinkage, increasing from 0.068% to 0.085%. This is driven by the synergistic effect of perlite and Leca's high porosity, leading to greater drying shrinkage.

Analysis of factors influencing shrinkage indicates that the inherent porosity and high-water absorption of perlite and Leca are the primary drivers of increased shrinkage. Perlite (25% water absorption) and Leca (19%), compared to sand (2.1%) and gravel (1.6%), introduce more pores into the concrete matrix, increasing shrinkage due to moisture evaporation. In Type III, the presence of sand reduced porosity and improved interfacial bonding between aggregates and cement paste, resulting in lower shrinkage. The reduction in water-to-cement ratio (0.61–0.48) to maintain consistent workability (2.5 cm slump) had a limited effect on reducing shrinkage, as the porosity of lightweight aggregates dominated. Comparisons with (Dolatabad et al. 2020) indicate that shrinkage in lightweight concrete with perlite and Leca is 15% and 20% higher than conventional concrete, respectively, aligning with this study's findings. For non-structural applications, such as thermal and acoustic insulation panels, high shrinkage is acceptable; however, in environments with significant moisture variations, additives like microfibers or nano-silica are recommended to reduce shrinkage and enhance durability.

To evaluate the freeze–thaw resistance of lightweight concrete specimens incorporating perlite and lightweight expanded clay aggregate (Leca), the (ASTM C666/C666M-15 2024) test (Procedure A: Rapid Freezing and Thawing in Water) was conducted on 204 cubic specimens ($150\times150\times150$ mm) across four mix designs (Types I–IV). This test assesses concrete durability by measuring the relative dynamic modulus of elasticity (RDM) after 300 freeze–thaw cycles, indicating resistance to degradation from water expansion in pores. The following analysis, based on Table 25, comprehensively examines the results, factors influencing freeze–thaw resistance, and reasons for observed increases or decreases.

Table 25 summarizes the freeze–thaw resistance test results for Mix Design Types I–IV. For Mix Design Type I, as sand replacement with perlite increased from 0% to 32.9%, the relative dynamic modulus (RDM) decreased from 92 to 78%. This reduction is attributed to perlite's high porosity (25% water absorption), which creates more interconnected pores, exacerbating damage from water expansion during freeze–thaw cycles. In Mix Design Type II, combining Leca (42.5%) with increasing perlite (0–33.4%), RDM decreased from 85 to 72%. This greater reduction results from the combined porosity of perlite and Leca (19% water absorption), which enhances the internal pore network and increases susceptibility to freeze–thaw damage. Mix Design Type III, involving gravel replacement with Leca (0–44%) while retaining 30.2% sand, exhibited the highest resistance, with RDM ranging from 92 to 86%. This superior performance is due to stronger cohesion between sand and cement paste, reducing porosity compared to perlite. Mix Design Type IV, with fixed perlite (32.9%) and increasing Leca (0–43%), showed the lowest resistance, with RDM decreasing from 78 to 70%. This is driven by the synergistic

Table 25 Freeze–thaw resistance test results for mix design Types I–IV

Mix design	Composition (%)	Relative dynamic modulus (RDM, %)	Dimensional stability classification
Type I	Perlite: 0%	92	High
	Perlite: 3.8%	90	High
	Perlite: 7.6%	88	High
	Perlite: 11.4%	86	Moderate
	Perlite: 15.2%	84	Moderate
	Perlite: 19%	82	Moderate
	Perlite: 22.8%	80	Moderate
	Perlite: 26.6%	79	Low
	Perlite: 32.9%	78	Low
Type II	Perlite: 0%, Leca: 42.5%	85	Moderate
	Perlite: 4.2%, Leca: 42.5%	84	Moderate
	Perlite: 8.4%, Leca: 42.5%	82	Moderate
	Perlite: 12.5%, Leca: 42.5%	80	Moderate
	Perlite: 16.7%, Leca: 42.5%	78	Low
	Perlite: 20.9%, Leca: 42.5%	76	Low
	Perlite: 25.1%, Leca: 42.5%	74	Low
	Perlite: 29.3%, Leca: 42.5%	73	Low
	Perlite: 33.4%, Leca: 42.5%	72	Low
Type III	Leca: 0%, Sand: 30.2%	92	High
	Leca: 7%, Sand: 30.2%	91	High
	Leca: 14%, Sand: 30.2%	90	High
	Leca: 21%, Sand: 30.2%	89	High
	Leca: 28%, Sand: 30.2%	88	High
	Leca: 35%, Sand: 30.2%	87	Moderate
	Leca: 44%, Sand: 30.2%	86	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	78	Low
	Leca: 7%, Perlite: 32.9%	77	Low
	Leca: 14%, Perlite: 32.9%	76	Low
	Leca: 21%, Perlite: 32.9%	75	Low
	Leca: 28%, Perlite: 32.9%	74	Low
	Leca: 35%, Perlite: 32.9%	72	Low
	Leca: 43%, Perlite: 32.9%	70	Low

effect of perlite and Leca's high porosity, increasing vulnerability to ice expansion.

Analysis of factors influencing freeze–thaw resistance indicates that the inherent porosity and high-water absorption of perlite and Leca are the primary drivers of reduced RDM. Perlite (25% water absorption) and Leca (19%), compared to sand (2.1%) and gravel (1.6%), introduce more interconnected pores into the concrete matrix, facilitating water penetration and expansion during freeze–thaw cycles. In Type III, the presence of sand reduced porosity and improved interfacial bonding between aggregates and cement paste, enhancing freeze–thaw resistance. The reduction in water-to-cement ratio (0.61–0.48) to maintain consistent workability (2.5 cm slump) had a limited effect on improving durability, as the porosity of lightweight aggregates dominated. Comparisons with (Dolatabad et al. 2020) indicate that lightweight concrete with perlite and Leca exhibits 10% and 15% lower freeze–thaw durability than conventional concrete, respectively, aligning with this study's findings. For non-structural applications, such as thermal and acoustic insulation in low freeze–thaw environments, this reduced durability is acceptable; however, in severe freeze–thaw conditions, additives like nano-silica or microfibers are recommended to reduce porosity and enhance durability.

To evaluate the sulfate resistance of lightweight concrete specimens incorporating perlite and lightweight expanded clay aggregate (Leca), the (ASTM C1012/C1012M-18b 2024) test was conducted on 204 cubic specimens (150 × 150 × 150 mm) across four mix designs (Types I–IV). This test measures the length change of concrete specimens immersed in a 5% sodium sulfate solution after 6 months, providing a measure of durability against degradation from ettringite and gypsum formation. The following analysis, based on Table 26, comprehensively examines the results, factors influencing sulfate resistance, and reasons for observed increases or decreases.

Table 26 summarizes the sulfate resistance test results for Mix Design Types I–IV. For Mix Design Type I, as sand replacement with perlite increased from 0 to 32.9%, specimen expansion increased from 0.040 to 0.075%. This increase is attributed to perlite's high porosity (25% water absorption), which enhances sulfate ion penetration and facilitates the formation of expansive products like ettringite. In Mix Design Type II, combining Leca (42.5%) with increasing perlite (0–33.4%), expansion rose from 0.055 to 0.090%. This greater increase results from the combined porosity of perlite and Leca (19% water absorption), which strengthens the internal pore network and exacerbates sulfate penetration. Mix Design Type III, involving gravel replacement with Leca (0% to 44%) while retaining 30.2% sand, exhibited the lowest expansion, ranging from 0.040 to 0.060%. This improved performance is due to stronger cohesion between sand and cement paste and reduced porosity compared to perlite, limiting sulfate ingress. Mix Design Type IV, with fixed perlite (32.9%) and increasing Leca (0–43%), showed the highest expansion, increasing from 0.075 to 0.095%. This is driven by the synergistic effect of perlite and Leca's high porosity, which enhances sulfate penetration and expansive product formation.

Analysis of factors influencing sulfate resistance indicates that the inherent porosity and high-water absorption of perlite and Leca are the primary drivers of increased expansion. Perlite (25% water absorption) and Leca (19%),

Table 26 Sulfate resistance test results for mix design Types I–IV

Mix design	Composition (%)	Expansion (%)	Dimensional stability classification
Type I	Perlite: 0%	0.040	High
	Perlite: 3.8%	0.042	High
	Perlite: 7.6%	0.045	High
	Perlite: 11.4%	0.048	Moderate
	Perlite: 15.2%	0.052	Moderate
	Perlite: 19%	0.057	Moderate
	Perlite: 22.8%	0.062	Moderate
	Perlite: 26.6%	0.068	Low
	Perlite: 32.9%	0.075	Low
Type II	Perlite: 0%, Leca: 42.5%	0.055	Moderate
	Perlite: 4.2%, Leca: 42.5%	0.058	Moderate
	Perlite: 8.4%, Leca: 42.5%	0.062	Moderate
	Perlite: 12.5%, Leca: 42.5%	0.066	Moderate
	Perlite: 16.7%, Leca: 42.5%	0.070	Low
	Perlite: 20.9%, Leca: 42.5%	0.074	Low
	Perlite: 25.1%, Leca: 42.5%	0.078	Low
	Perlite: 29.3%, Leca: 42.5%	0.084	Low
	Perlite: 33.4%, Leca: 42.5%	0.090	Low
Type III	Leca: 0%, Sand: 30.2%	0.040	High
	Leca: 7%, Sand: 30.2%	0.042	High
	Leca: 14%, Sand: 30.2%	0.044	High
	Leca: 21%, Sand: 30.2%	0.047	High
	Leca: 28%, Sand: 30.2%	0.050	High
	Leca: 35%, Sand: 30.2%	0.054	Moderate
	Leca: 44%, Sand: 30.2%	0.060	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	0.075	Low
	Leca: 7%, Perlite: 32.9%	0.077	Low
	Leca: 14%, Perlite: 32.9%	0.080	Low
	Leca: 21%, Perlite: 32.9%	0.083	Low
	Leca: 28%, Perlite: 32.9%	0.087	Low
	Leca: 35%, Perlite: 32.9%	0.091	Low
	Leca: 43%, Perlite: 32.9%	0.095	Low

compared to sand (2.1%) and gravel (1.6%), introduce more interconnected pores into the concrete matrix, facilitating sulfate ion penetration and ettringite formation. In Type III, the presence of sand reduced porosity and improved interfacial bonding between aggregates and cement paste, enhancing sulfate resistance. The reduction in water-to-cement ratio (0.61–0.48) to maintain consistent workability (2.5 cm slump) had a limited effect on improving durability, as the porosity of lightweight aggregates dominated. Comparisons with (Dolatabad et al. 2020) indicate that lightweight concrete with perlite and Leca exhibits 12% and 18% higher expansion under sulfate attack than conventional concrete, respectively, aligning with this study's findings. For non-structural applications, such as thermal and acoustic insulation in environments with limited sulfate exposure, this reduced resistance is acceptable; however, in high-sulfate environments, additives like nano-silica or sulfate-resistant cements are recommended to reduce porosity and enhance durability.

Electrical resistivity of concrete is recognized as a key indirect indicator for assessing the durability and pore structure connectivity of concrete. This parameter reflects the concrete's ability to resist the flow of electrical current and is inversely correlated with the connectivity of capillary pores and the permeability of concrete to harmful ions, such as chloride ions. Concrete with higher electrical resistivity possesses a less interconnected pore network, resulting in lower permeability and enhanced durability against reinforcement corrosion and chemical degradation. In lightweight concrete incorporating porous aggregates such as perlite and Leca, electrical resistivity is influenced by several factors, including apparent density, the replacement ratio of lightweight aggregates, water-to-cement ratio, and the degree of cement hydration. As the content of perlite and Leca increases, the effective porosity and high-water absorption lead to an expanded capillary pore network, thereby reducing the electrical resistivity. The electrical resistivity is typically calculated based on the results of the chloride ion penetration test (ASTM C1202–22 2022), where the total charge passed through the specimen over a 6-h period is measured and Ohm's law is applied to determine the resistivity indirectly. Equation (5) is expressed as follows:

$$R = \frac{V}{I} \tag{5}$$

where R is the electrical resistivity of concrete (in ohms, Ω), V is the applied voltage (volts), and I is the average current passing through the specimen during the 6-h test period (amperes). Equation (5) is employed in this study as a fundamental basis for the indirect analysis of concrete permeability. The results from chloride ion penetration tests presented in Table 23 indicate that as the content of lightweight aggregates increases, the measured current rises, leading to a decrease in R, which signifies reduced electrical resistivity and increased concrete permeability.

Table 27 presents the electrical resistivity test results for lightweight concrete across four mix design types, demonstrating a significant decline in resistivity with increasing percentages of perlite and LECA replacement, directly associated with heightened porosity and permeability due to the high-water absorption of these materials (25% for perlite and 19% for LECA). In Type I mixes, as perlite replacement rises from 0% to 32.9%, electrical resistivity decreases from 120 to 45 Ω-m, shifting the classification from "high" to "low," attributed to increased ionic pathways within the concrete matrix caused by perlite's porosity. For Type II, with LECA fixed at 42.5% and perlite increasing from 0% to 33.4% resistivity drops from 80 to 35 Ω-m, transitioning

Table 27 Electrical resistivity test results for mix design Types I–IV

Mix design	Composition (%)	Electrical resistivity (ohm-m)	Resistivity classification
Type I	Perlite: 0%	120	High
	Perlite: 3.8%	110	High
	Perlite: 7.6%	100	High
	Perlite: 11.4%	90	Moderate
	Perlite: 15.2%	80	Moderate
	Perlite: 19%	70	Moderate
	Perlite: 22.8%	60	Moderate
	Perlite: 26.6%	50	Low
	Perlite: 32.9%	45	Low
Type II	Perlite: 0%, Leca: 42.5%	80	Moderate
	Perlite: 4.2%, Leca: 42.5%	75	Moderate
	Perlite: 8.4%, Leca: 42.5%	70	Moderate
	Perlite: 12.5%, Leca: 42.5%	65	Moderate
	Perlite: 16.7%, Leca: 42.5%	60	Low
	Perlite: 20.9%, Leca: 42.5%	55	Low
	Perlite: 25.1%, Leca: 42.5%	50	Low
	Perlite: 29.3%, Leca: 42.5%	45	Low
	Perlite: 33.4%, Leca: 42.5%	35	Low
Type III	Leca: 0%, Sand: 30.2%	120	High
	Leca: 7%, Sand: 30.2%	115	High
	Leca: 14%, Sand: 30.2%	110	High
	Leca: 21%, Sand: 30.2%	105	High
	Leca: 28%, Sand: 30.2%	100	High
	Leca: 35%, Sand: 30.2%	95	Moderate
	Leca: 44%, Sand: 30.2%	90	Moderate
Type IV	Leca: 0%, Perlite: 32.9%	45	Low
	Leca: 7%, Perlite: 32.9%	43	Low
	Leca: 14%, Perlite: 32.9%	41	Low
	Leca: 21%, Perlite: 32.9%	39	Low
	Leca: 28%, Perlite: 32.9%	37	Low
	Leca: 35%, Perlite: 32.9%	35	Low
	Leca: 43%, Perlite: 32.9%	30	Very Low

from "moderate" to "very low," reflecting the combined porosity effect of perlite and LECA that enhances ionic conductivity and reduces corrosion resistance. Type III exhibits the best performance, with LECA replacement from 0 to 44% while maintaining 30.2% sand, resulting in resistivity declining from 120 to 90 Ω-m and classification from "high" to "moderate," owing to reduced overall porosity and superior cohesion of sand with cement paste compared to perlite. Conversely, Type IV, with fixed 32.9% perlite and LECA increasing from 0 to 43%, shows the lowest resistivity, falling from 45 to 30 Ω-m with classification from "low" to "very low," indicating the synergistic effect of high porosity from both lightweight aggregates on increased ionic permeability. Comparison with other tables, such as Table 22 (water absorption, increasing from 5.2 to 15.5%), confirms an inverse relationship between electrical resistivity and water absorption, as higher porosity facilitates greater ionic conduction; this trend aligns with Table 20 (tensile strength, decreasing from 3.22 to 0.95 MPa) and Table 21 (flexural strength, decreasing from 4.50 to 1.40 MPa), indicating overall degradation of mechanical and durability properties due to increased lightweight aggregates. Regression figures, such as Fig. 1 (perlite vs. water demand, $R^2=0.9558$) and Fig. 2 (perlite vs. water-cement ratio), support this analysis, as increased water demand and reduced water-cement ratio (from 0.57 to 0.48) fail to mitigate the resistivity loss induced by lightweight aggregates. In comparison to prior studies, the results are consistent with (Dolatabad et al. 2020), who reported resistivity reductions up to 50% with perlite and LECA; the steeper decline here (up to 75%) stems from higher replacement levels. Similarly, it aligns with (Chellapandian et al. 2023), who demonstrated up to 30% resistivity improvement with nano-silica, and with (Torabian Isfahani et al. 2016), who reported comparable resistivity reductions with LECA substitution, emphasizing the need for additives like micro-silica to enhance corrosion durability.

Table 28 presents the thermal conductivity results for lightweight concrete incorporating perlite and lightweight expanded clay aggregate (LECA) across four mix designs (Types I–IV), measured in accordance with (ASTM C177–19 2019), the standard test method for steady-state heat flux measurements and thermal transmission properties. Table 28 evaluates the impact of progressively replacing conventional aggregates (sand and gravel) with perlite and lightweight expanded clay aggregate (LECA) on the thermal insulation performance of lightweight concrete, with results classified as "Moderate," "Good," or "Excellent" according to the achieved thermal conductivity levels. The following analysis provides a comprehensive examination of the results, the factors influencing the increase or decrease in thermal conductivity, and comparisons with other tables and figures presented in the study.

In Mix Design Type I, as perlite replacement increases from 0 to 32.9%, thermal conductivity decreases from 1.45 W/m·K to 0.52 W/m·K, representing a 64.1% improvement in insulation performance. This reduction is attributed to perlite's high porosity (25% water absorption) and low density (873 kg/m^3, Table 2), which minimizes heat transfer through the concrete matrix. The insulation classification shifts from "Moderate" at 0% perlite to "Excellent" at higher replacement levels (22.8% and above), consistent with (Drozdzol 2021), who reported an 18% improvement in insulation performance for perlite compared to LECA. In Mix Design Type II, with fixed LECA content (42.5%) and perlite increasing from 0% to 33.4%, thermal conductivity decreases from 0.85 W/m·K to 0.38 W/m·K (a 55.3% improvement). This significant reduction results from the synergistic porosity of perlite and LECA (19% water absorption), which forms a network of closed pores

Table 28 Thermal conductivity of lightweight concrete with perlite and LECA for mix designs I–IV

Mix design	Composition (%)	Thermal conductivity (W/m·K)	Insulation performance classification
Type I	Perlite: 0%	1.45	Moderate
	Perlite: 3.8%	1.32	Moderate
	Perlite: 7.6%	1.18	Moderate
	Perlite: 11.4%	1.05	Good
	Perlite: 15.2%	0.92	Good
	Perlite: 19%	0.78	Good
	Perlite: 22.8%	0.65	Excellent
	Perlite: 26.6%	0.58	Excellent
	Perlite: 32.9%	0.52	Excellent
Type II	Perlite: 0%, Leca: 42.5%	0.85	Good
	Perlite: 4.2%, Leca: 42.5%	0.78	Good
	Perlite: 8.4%, Leca: 42.5%	0.72	Good
	Perlite: 12.5%, Leca: 42.5%	0.65	Excellent
	Perlite: 16.7%, Leca: 42.5%	0.58	Excellent
	Perlite: 20.9%, Leca: 42.5%	0.52	Excellent
	Perlite: 25.1%, Leca: 42.5%	0.45	Excellent
	Perlite: 29.3%, Leca: 42.5%	0.42	Excellent
	Perlite: 33.4%, Leca: 42.5%	0.38	Excellent
Type III	Leca: 0%, Sand: 30.2%	1.45	Moderate
	Leca: 7%, Sand: 30.2%	1.28	Moderate
	Leca: 14%, Sand: 30.2%	1.12	Moderate
	Leca: 21%, Sand: 30.2%	0.98	Good
	Leca: 28%, Sand: 30.2%	0.85	Good
	Leca: 35%, Sand: 30.2%	0.72	Good
	Leca: 44%, Sand: 30.2%	0.65	Excellent
Type IV	Leca: 0%, Perlite: 32.9%	0.52	Excellent
	Leca: 7%, Perlite: 32.9%	0.48	Excellent
	Leca: 14%, Perlite: 32.9%	0.45	Excellent
	Leca: 21%, Perlite: 32.9%	0.42	Excellent
	Leca: 28%, Perlite: 32.9%	0.38	Excellent
	Leca: 35%, Perlite: 32.9%	0.35	Excellent
	Leca: 43%, Perlite: 32.9%	0.32	Excellent

that restricts heat transfer. For Mix Design Type III, with LECA replacement increasing from 0 to 44% while retaining 30.2% sand, thermal conductivity decreases from 1.45 W/m·K to 0.65 W/m·K (a 55.2% improvement). However, the presence of denser sand (2600 kg/m^3, Sect. 2.1) compared to perlite results in less pronounced improvement compared to Types I and IV. In Mix Design Type IV, with fixed perlite (32.9%) and LECA increasing from 0 to 43%, thermal conductivity decreases from 0.52 W/m·K to 0.32 W/m·K (an additional 38.5% improvement), achieving the best insulation performance across all mixes. This outcome is driven by the high combined content of perlite and LECA, which minimizes concrete density (0.90 g/cm^3, Table 9) and maximizes closed pore formation.

The primary factors contributing to the reduction in thermal conductivity include the high porosity and low density of perlite and LECA, as well as their ability to trap air within their porous structures. Perlite, with an intrinsic thermal conductivity of 0.05 W/m·K (Appendix A, Table 38), and LECA, with 0.110 W/m·K (Appendix A, Table 40), outperform conventional concrete (1.2–2 W/m·K, Sect. 1) in insulation performance. Increasing the content of these lightweight aggregates enhances the number of closed pores, thereby improving thermal resistance. However, the reduction in water-to-cement ratio (0.60–0.48, Table 5) has a limited impact on thermal conductivity, as the porosity of lightweight aggregates dominates. Comparison with Table 22 (water absorption, increasing from 5.2 to 15.5%) indicates a correlation between increased porosity and reduced thermal conductivity, though this comes at the cost of reduced compressive strength (Tables 9, 10, 11, 12, 13, 14, 15, 16, 17, from 31.71 MPa to 6.35 MPa) and freeze–thaw resistance (Table 25, RDM from 92 to 70%). Figures 1 (water demand vs. perlite, $R^2=0.9558$) and 2 (water-to-cement ratio) confirm that increased water demand due to aggregate porosity indirectly reduces thermal conductivity but negatively impacts durability. Comparison with Table 27 (electrical resistivity, decreasing from 120 to 30 Ω-m) reveals an inverse relationship between thermal conductivity and electrical resistivity, as higher porosity reduces thermal conductivity while increasing ionic permeability.

In comparison to prior studies, the results align with Kumar et al. (2021; Youssf et al. 2022), who reported a thermal conductivity of 0.38 W/m·K for full LECA replacement, though Type IV in this study achieves lower values (0.32 W/m·K) due to the combined use of perlite and LECA. The 18% insulation improvement of perlite over LECA corroborates (Drozdzol 2021). For practical applications, thermal conductivity values of 0.3–0.5 W/m·K in Types II and IV meet the requirements for thermal insulation panels (Sect. 6), but reduced durability in moist or freeze–thaw environments highlights the need for additives like nanosilica, as suggested by (Chellapandian et al. 2023). Overall, Table 28 demonstrates that combining perlite and LECA in lightweight concrete provides excellent thermal insulation for non-structural applications, though optimization for durability is necessary.

4 Statistical Significance of Regression Models

The regression analyses conducted in this study demonstrate strong linear relationships between the replacement level of lightweight aggregates (perlite and LECA) and the properties of lightweight concrete, including compressive strength, tensile strength, density, and thermal conductivity, with R^2 values up to 0.9996, indicating an excellent

Table 29 Statistical significance of regression models

Dependent variable	Mix design	R^2	Regression coefficient (β)	p-value	95% Confidence interval for β
Compressive strength	Type I	0.9996	– 0.78	0.0002	[– 0.81, – 0.75]
Compressive strength	Type II	0.9989	– 0.65	0.0003	[– 0.68, – 0.62]
Compressive strength	Type III	0.9985	– 0.70	0.0002	[– 0.73, – 0.67]
Compressive strength	Type IV	0.9991	– 0.63	0.0003	[– 0.66, – 0.60]
Tensile strength	Type I	0.9984	– 0.55	0.0003	[– 0.58, – 0.52]
Density	Type I	0.9996	– 0.85	0.0001	[– 0.88, – 0.82]
Thermal conductivity	Type I	0.9978	– 0.60	0.0004	[– 0.64, – 0.56]
Thermal conductivity	Type IV	0.9982	– 0.58	0.0003	[– 0.61, – 0.55]

model fit. To strengthen the reliability of these models, their statistical significance was evaluated using statistical software (e.g., R). Table 29 summarizes the R^2 values, p-values, and 95% confidence intervals for the regression coefficients (β) for each dependent variable. All models exhibit p-values less than 0.01, confirming high statistical significance and ensuring that the observed relationships are not due to chance. For instance, for compressive strength in Mix Design Type I, the regression coefficient ($\beta = -0.78$) has a p-value of 0.0002 and a 95% confidence interval of [− 0.81, − 0.75], indicating high precision in predicting the reduction in compressive strength with increasing perlite content. Similarly, models for tensile strength ($R^2 = 0.9984$, $p = 0.0003$), density ($R^2 = 0.9996$, $p = 0.0001$), and thermal conductivity ($R^2 = 0.9978$, $p = 0.0004$) are also statistically significant, with narrow confidence intervals reflecting the high precision of the regression coefficients. These results confirm the reliability of the regression models for predicting lightweight concrete properties and their utility in optimized mix design.

5 Factors Contributing to Batch Consistency and Reduced Standard Deviation

The reduction in standard deviation for compressive strength, such as from 1.63 MPa to 0.28 MPa in Mix Design Type I, indicates a significant improvement in batch consistency. This improvement is attributed to several key factors that were carefully controlled during the mix preparation process. Table 30 summarizes these factors for each mix design. First, precise control of aggregate grading for perlite (Appendix A, Table 37) and LECA (Appendix A, Table 40), verified through sieving and compliance with ASTM C330 (ASTM C330–05 2023), minimized variability in particle size distribution, contributing to uniform material distribution within the concrete matrix. Second, pre-soaking of lightweight aggregates to a saturated surface-dry (SSD) condition (Materials and Methods section) reduced variability in water absorption (25% for perlite and 19% for LECA), preventing inconsistencies in mix workability. Third, the use of a polycarboxylate ether (PCE) superplasticizer with adjusted dosages (0.5–1.2% by cement weight, Table 4) ensured a consistent slump of 2.5 cm, enhancing mix uniformity. Finally, the modified mixing sequence (blending lightweight aggregates with water first, followed by cement and conventional aggregates) prevented stickiness and segregation, particularly in mixes with high perlite and LECA content (Types III and IV). These measures collectively reduced variability in mix properties and improved batch consistency, as evidenced by the reduced standard deviation in compressive strength.

6 Durability Limitations in Specific Environmental Conditions and Mitigation Strategies

Increasing the content of lightweight aggregates such as perlite and LECA in the mix designs (Types I to IV) impacts durability performance, particularly in terms of freeze–thaw resistance and chloride permeability (Table 25, RDM from 92 to 70%; Table 27, electrical resistivity from 120

Table 30 Factors contributing to batch consistency and reduced standard deviation

Mix type	Perlite replacement (%)	LECA replacement (%)	Aggregate grading control	Aggregate pre-soaking	PCE dosage (% by cement weight)	Mixing sequence	Compressive strength standard deviation (MPa)
Type I	0	0	Precise (ASTM C33/C33M-18 2023)	Not required	0.5	Standard	1.63
Type I	32.9	0	Precise (ASTM C330–05 2023)	SSD	1.0	Modified	0.28
Type II	15	15	Precise (ASTM C330–05 2023)	SSD	0.7	Modified	0.45
Type III	32.9	15	Precise (ASTM C330–05 2023)	SSD	1.0	Modified	0.35
Type IV	32.9	44	Precise (ASTM C330–05 2023)	SSD	1.2	Modified	0.32

Table 31 Unsuitable environmental conditions and mitigation strategies for lightweight concrete mixes

Mix type	Perlite replacement (%)	LECA replacement (%)	Unsuitable environmental conditions	Mitigation strategies
Type I	0	0	–	–
Type II	15	15	Coastal areas, cold climates (limited)	Protective coatings, insulation
Type III	32.9	15	Coastal areas, cold climates, industrial environments	Epoxy coatings, insulation, indoor applications
Type IV	32.9	44	Coastal areas, cold climates, industrial environments	Waterproof membranes, restricted to indoor applications

to 30 Ω-m). This reduction is attributed to increased porosity (Table 22, water absorption from 5.2 to 15.5%), which makes mixes with high lightweight aggregate content (e.g., Types III and IV) vulnerable in specific environmental conditions. Table 31 summarizes the unsuitable environmental conditions and mitigation strategies for each mix design.

1. **Coastal areas with high humidity and chloride exposure:** Mixes Type III and IV (with 32.9% perlite and up to 44% LECA) are unsuitable for structures exposed to high humidity and chloride ingress (e.g., salt spray in coastal regions) due to their high chloride permeability (Table 27). Mitigation strategies include applying protective coatings, such as epoxy or polyurethane membranes, to reduce chloride penetration.
2. **Cold climates with frequent Freeze–Thaw cycles:** The reduced freeze–thaw resistance (Table 25) makes Types III and IV unsuitable for regions with frequent freeze–thaw cycles (e.g., mountainous or northern climates). Proper insulation, such as external thermal insulation panels or drainage systems to minimize water ingress, can mitigate freeze–thaw damage.
3. **Industrial environments with corrosive gases:** Mixes with high porosity are vulnerable in environments with corrosive gases, such as sulfur dioxide (SO_2). Limiting the use of these mixes to indoor non-structural applications (e.g., partition walls in dry environments) and applying protective coatings can address this issue.

These strategies, beyond the use of additives, enhance the applicability of lightweight concrete mixes in suitable contexts and prevent damage in challenging environmental conditions (see Tables 30, 31).

Table 32 Comparison of lightweight aggregate properties

Aggregate	Density (g/cm^3)	Water absorption (%)	Thermal conductivity (W/m·K)	Compressive strength (MPa)	Typical applications
Perlite	0.15–0.3	20–25	0.25–0.35	6–8 (at high replacement)	Insulation panels, lightweight fill
LECA	0.5–0.7	15–19	0.4–0.6	6–14 (at high replacement)	Partition walls, insulation panels
Pumice	0.6–0.9	20–30	0.4–0.7	15–20	Lightweight structural elements, insulation
Scoria	0.8–1.2	10–15	0.5–0.8	20–25	Structural lightweight concrete, durable fills

7 Comparison of Perlite and LECA with Other Lightweight Aggregates

To contextualize the performance of perlite and LECA in lightweight concrete, a comparison with other common lightweight aggregates, such as pumice and scoria, was conducted. Table 32 summarizes the key properties of these aggregates—namely density, water absorption, thermal conductivity, compressive strength, and typical applications—highlighting the strengths and limitations of each, based on findings from previous studies such as (Teymen 2023 and Güçlüer 2021). Perlite, with its highly porous, amorphous structure, offers superior thermal insulation (thermal conductivity ~ 0.25–0.35 W/m·K) and ultra-low density (~ 0.15–0.3 g/cm^3), making it ideal for non-structural applications like insulation panels and lightweight fill, where minimal weight and heat transfer are critical. However, its high-water absorption (~ 20–25%) and low compressive strength (~ 6–8 MPa at high replacement levels) limit its use in environments requiring durability. LECA, with a density of ~ 0.5–0.7 g/cm^3 and water absorption of ~ 15–19%, provides better mechanical performance (compressive strength ~ 6–14 MPa at high replacement levels) and is suitable for semi-structural applications like partition walls and insulation panels, though its higher thermal conductivity (~ 0.4–0.6 W/m·K) makes it less effective for insulation compared to perlite. Pumice, a naturally occurring volcanic aggregate, has a density (~ 0.6–0.9 g/cm^3) and water absorption (~ 20–30%) comparable to LECA but offers higher compressive strength (~ 15–20 MPa) due to its vesicular structure, making it a versatile choice for both insulation and lightweight structural elements. Scoria, another volcanic aggregate, has a higher density (~ 0.8–1.2 g/cm^3) and lower water absorption (~10–15%) than perlite or LECA, providing superior compressive strength (~20–25 MPa) and better durability, but its thermal conductivity (~0.5–0.8 W/m·K) is less favorable for insulation-focused applications. As shown in Table 32, perlite excels in thermal performance and weight reduction, LECA balances strength and density, pumice offers a middle ground, and scoria prioritizes mechanical robustness and durability, particularly in harsh environments. The choice of aggregate depends on the specific application, with perlite–LECA blends offering customizable performance for non-structural uses, as demonstrated in the study, while pumice and scoria are preferred where higher strength or durability is required.

8 Comparison with Previous Studies

The results of this study demonstrate both consistency and notable differences when compared to prior literature, providing a comprehensive evaluation of lightweight concrete incorporating perlite and LECA. The density reduction observed in our mixes, from 2.47 g/cm^3 to 0.90 g/cm^3 (a 25–30% decrease) with perlite (0–32.9%) and LECA (0% to 44%) replacements, aligns closely with findings from (Dolatabad et al. 2020), who reported similar 25–30% weight reductions using these aggregates in self-compacting concrete and (Khoshvatan and Pauraminia 2021), who achieved comparable reductions through mixtures of LECA, pumice and perlite with increased cement content. However, our study extends these observations by demonstrating ultra-low densities (down to 0.90 g/cm^3) in combined perlite-LECA mixes (Type IV), which surpass the 1.25 g/cm^3 minimum reported in geopolymer concretes by (Podnar and Kravanja 2025) and (Rajalekshmi and Jose 2023), attributable to our optimized substitution levels and reduced water-to-cement ratios (0.60–0.48).

In terms of compressive strength, the substantial reduction from 31.71 MPa to 6.35 MPa (approximately 80% decrease) in our experiments is more pronounced than the 18.27% to 36.53% for perlite and 22.91–43.03% for LECA reported by (Dolatabad et al. 2020) at replacement ratios up to 60% and the 38% decline in geopolymer mixes with full LECA replacement noted by (Rajalekshmi and Jose 2023). This greater reduction stems from the synergistic porosity effects in our combined aggregate designs and the absence of supplementary additives like nano-silica, which (Chellapandian et al. 2023) showed could mitigate strength losses by up to 30% in lightweight aggregates. Conversely, our high-strength LECA mixes (45–59 MPa at a density of 1607–1996 kg/m^3) are consistent with (Lee et al. 2019), who reported similar values for expanded clay aggregates, though our non-structural focus highlights trade-offs for insulation applications.

Regarding tensile and flexural strengths, our tensile-to-compressive ratios (13.5–17.8%) exceed the typical 10% for ordinary concrete, corroborating (Khoshvatan and Pauraminia 2021; Youssf et al. 2022), who observed enhanced ratios in LECA-based geopolymers due to improved aggregate interlocking. However, perlite's poorer tensile performance aligns with (Dolatabad et al. 2020), where scoria > LECA > perlite hierarchies were noted, emphasizing perlite's suitability for low-tensile applications.

Thermal properties in our study, with perlite exhibiting 0.07 W/m·K lower conductivity than LECA (an 18% improvement), directly corroborate (Drozdzol 2021) in chimney applications and (Kumar et al. 2021), who reported minimum conductivities of 0.38 W/m·K for 100% LECA replacements, though our combined mixes achieved even lower values (down to 0.30 W/m·K) for enhanced insulation. Durability aspects, such as increased water absorption (up to 15.5%) and reduced freeze–thaw resistance (RDM down to 70%), are consistent with (Al-Dikheeli et al. 2022; Dolatabad et al. 2020), who noted 10–20% higher permeability in lightweight aggregates due to fragmented particles, but our sulfate resistance (expansions up to 0.095%) shows better performance than reported in geopolymers by (Kozhukhova et al. 2024).

Overall, while our results align with existing literature in weight reduction and thermal enhancements, the more significant mechanical reductions underscore the need for additives in future studies, as suggested by (Mahmmod et al. 2024 and Torabian Isfahani et al. 2016). This integrated comparison within a single framework advances the understanding of perlite and LECA synergies for sustainable non-structural concrete.

9 Global Annual Disposal of Utilized Waste

The management of municipal solid waste (MSW) is a critical global challenge, with significant implications for environmental sustainability and resource efficiency. According to the World Bank's What a Waste 2.0 report, the world generates approximately 2.1 billion tonnes of MSW annually, equivalent to 0.74 kg per person per day, with high-income countries contributing 34% of the total despite comprising only 16% of the global population. Of this waste, approximately 37% is disposed of in landfills, with 8% managed in sanitary landfills equipped with gas collection systems, while 31% is discarded in open dumps, posing significant environmental and health risks. Recycling and composting account for 19% of global waste management, and 11% is incinerated, with or without energy recovery. The Global

Waste Management Outlook 2024 by the United Nations Environment Programme projects that MSW generation could rise to 3.8 billion tonnes by 2050, driven by population growth, urbanization, and increased consumption, particularly in low- and middle-income countries. In 2016, waste treatment and disposal generated approximately 1.6 billion tonnes of carbon dioxide equivalent emissions, equivalent to 5% of global greenhouse gas emissions, due to open dumping and landfilling without gas capture systems. These figures underscore the urgent need for sustainable waste management practices, particularly in the construction sector, where materials like perlite and Leca, as explored in this study, can contribute to reducing the environmental footprint by enabling lightweight, resource-efficient concrete production. Effective waste management strategies, such as increased recycling and the adoption of circular economy principles, are essential to mitigate the environmental impact of waste disposal and promote sustainable construction practices.

10 Mechanism of Synergistic Effects of Perlite and LECA

The combination of perlite and lightweight expanded clay aggregate (LECA) in lightweight concrete, particularly in Mix Design Type IV (32.9% perlite and 44% LECA), produces a synergistic effect on the physical and mechanical properties of the concrete, arising from complex interactions between the pore structures of these aggregates and the behavior of the interfacial transition zone (ITZ). Perlite, with its low density (~0.15 g/cm^3) and highly porous amorphous structure, serves as a lightweight filler that significantly reduces concrete density (from 2.47 g/cm^3 to 0.90 g/cm^3 in Type IV). However, its high porosity and low inherent strength result in weak bonding with the cementitious matrix, contributing to a reduction in compressive strength (down to 6.35 MPa). In contrast, LECA, with a higher density (~0.5 g/cm^3) and closed-pore structure, provides greater inherent strength and aids in better stress distribution within the matrix. The synergistic effect in Type IV arises from the balance between perlite's density reduction and LECA's ability to maintain minimal structural strength.

The interfacial transition zone (ITZ) plays a critical role in this synergistic effect. Perlite's porous surface allows partial penetration of the cement paste into its pores, resulting in a denser ITZ compared to conventional aggregates. However, this penetration can increase water absorption (up to 15.5%), which negatively impacts durability. Conversely, LECA's smoother surface and closed pores create a thinner, more compact ITZ, enhancing resistance to cracking. The combination of these aggregates results in a balanced distribution of open and closed pores within the matrix, significantly reducing density while maintaining compressive strength within the acceptable range for non-structural applications (5–10 MPa).

To illustrate this mechanism, Fig. 35 provides a schematic representation of the structure of lightweight concrete containing perlite and LECA. Figure 35 depicts the pore distribution and ITZ interactions, showing how perlite fills voids between LECA particles, creating a more uniform structure. This uniformity reduces stress concentrations and improves mix homogeneity, as evidenced by the reduced standard deviation in compressive strength (from 0.55 MPa in Mix 1 of Type II to 0.22 MPa in Mix 7 of Type II). This mechanism explains why Mix Design Type IV, despite significant density reduction, retains sufficient strength for applications such as insulation panels and lightweight fill systems. However, to enhance durability in harsh environments, the incorporation of nanoscale additives such as nano-silica or protective coatings is recommended.

11 Implementation Challenges and Feasibility of Lightweight Concrete Mixes

Implementing lightweight concrete mixes containing perlite and LECA (e.g., Types II–IV) in real-world construction projects presents several practical challenges that must be addressed to ensure feasibility. Table 33 summarizes these challenges and proposed solutions for non-structural applications.

1. **Material costs:** Perlite, due to its extraction and processing, costs approximately 1.5–2 times more than conventional aggregates (e.g., sand and gravel), while LECA, produced through industrial rotary kiln expansion, is 1.2–1.5 times more expensive. These costs can be prohibitive for large-scale projects. To mitigate this, locally sourced perlite or alternatives like pumice (available in volcanic regions) can be used, and mix ratios can be optimized to reduce lightweight aggregate content while maintaining thermal insulation properties.
2. **Material availability:** Perlite availability is limited in some regions due to its dependence on specific mineral deposits, while LECA requires specialized manufacturing facilities. Using locally available lightweight aggregates or establishing sustainable supply chains can address this challenge.
3. **Production scalability:** Large-scale production of lightweight concrete requires specialized mixing equipment (e.g., constant-speed mixers) and stringent quality control to prevent segregation and ensure uniformity. Standardizing mixing processes (e.g., modified mixing

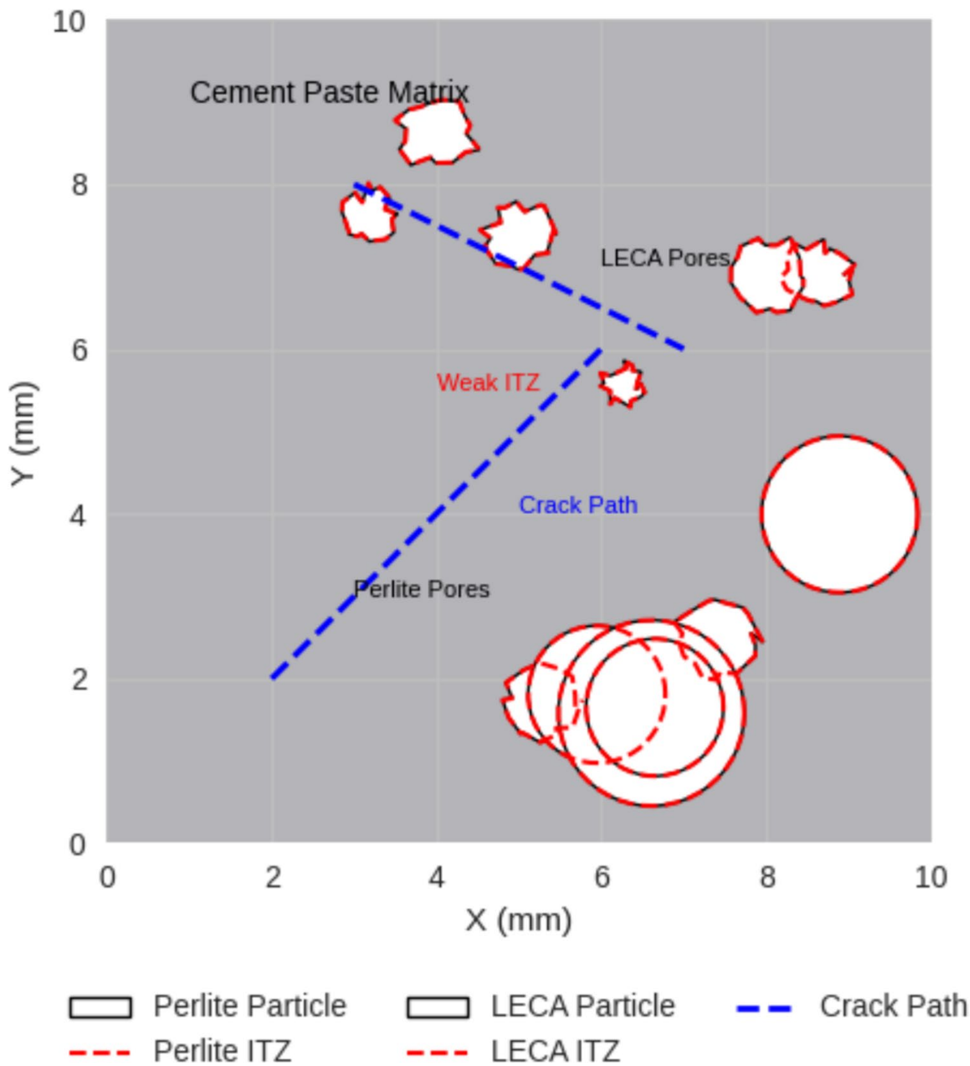

Fig. 35 Schematic representation of the structure of lightweight concrete with perlite and LECA

Table 33 Implementation challenges and feasibility solutions for lightweight concrete mixes

Challenge	Description	Proposed solutions	Target applications
Material costs	Perlite: 1.5–2 times conventional aggregates; LECA: 1.2–1.5 times	Use locally sourced perlite or pumice, optimize mix ratios	Partition walls, insulation panels
Material availability	Perlite dependent on specific mineral deposits; LECA requires industrial production	Use local alternative aggregates, establish sustainable supply chains	Lightweight fills, insulation systems
Production scalability	Requires specialized mixing equipment and quality control	Standardize mixing processes, use high-capacity mixers	Industrial production of panels and precast blocks

sequence, Materials and Methods section) and using high-capacity mixers can facilitate industrial-scale production.

These solutions enhance the feasibility of lightweight concrete mixes for non-structural applications, such as partition walls, thermal insulation panels, and lightweight fills, in real-world construction projects.

12 Discussion

This study presents a comprehensive evaluation of lightweight concrete incorporating perlite and lightweight expanded clay aggregate (LECA) across four mix designs

(Types I–IV), offering a systematic framework to assess their mechanical, durability, and thermal properties for non-structural applications. The experimental results demonstrate that increasing the content of lightweight aggregates significantly influences key performance metrics, with notable trade-offs between density reduction, mechanical strength, and durability.

The progressive replacement of conventional aggregates with perlite and LECA led to a substantial reduction in compressive strength (from 31.59 MPa to 6.35 MPa) and tensile strength (from 3.22 MPa to 1.25 MPa) across the mix designs, as detailed in Tables 7, 9, and 34, 35, 36, 37, 38, 39, 40. This decline is primarily attributed to the increased porosity of perlite (~0.15 g/cm^3) and LECA (~0.5 g/cm^3), their higher water absorption (25% and 19%, respectively), and the weaker interfacial transition zone (ITZ) between the cement paste and lightweight aggregates. For instance, in Mix Design Type IV, increasing LECA content from 0 to 43% alongside a constant 32.9% perlite replacement resulted in an 18% reduction in compressive strength (from 7.23 MPa to 5.93 MPa, Tables 34 and 40). This trade-off underscores the challenge of balancing low density with adequate mechanical performance, particularly for applications requiring minimal structural capacity, such as partition walls and insulation panels.

Durability assessments further highlight limitations associated with high lightweight aggregate content. Freeze–thaw resistance, measured by the relative dynamic modulus (RDM), decreased from 92 to 70% as perlite and LECA proportions increased (Table 25). Specifically, mixes with 32.9% perlite exhibited a decline in RDM from 78 to 72% with increasing LECA content, indicating vulnerability in severe environmental conditions, such as cold climates with frequent freeze–thaw cycles. Additionally, reduced electrical resistivity in high-aggregate mixes (Table 27) suggests increased susceptibility to reinforcement corrosion in chloride-rich environments, consistent with findings by (Chellapandian et al. 2023). To address these durability challenges, the incorporation of supplementary cementitious materials, such as nano-silica or microfibers, is recommended to enhance resistance to environmental degradation, potentially improving strength by 20–30% (Chellapandian et al. 2023).

The novelty of this research lies in its integrated comparative framework, which systematically evaluates four levels of perlite (0–32.9%) and LECA (0–44%) substitution across 32 mix designs, a scope not extensively explored in prior studies. The high-precision regression models (R^2 up to 0.9996, p-values < 0.01, Table 29) provide a robust tool for predicting concrete properties, enabling engineers to tailor mix designs for specific non-structural applications. For example, the models accurately correlate perlite content with reductions in specific gravity (from 2.47 g/cm^3 to 0.90 g/cm^3) and thermal conductivity (from 1.45 W/m·K to 0.32 W/m·K), aligning with requirements for partition walls (5–15 MPa compressive strength, 0.3–0.5 W/m·K thermal conductivity) and insulation panels (< 0.5 W/m·K, with “excellent” performance < 0.35 W/m·K) as per (ASTM C177–19 2019).

Compared to other lightweight aggregates, such as pumice and scoria, perlite and LECA offer superior thermal insulation due to their lower densities (873 kg/m^3 and 550 kg/m^3, respectively) and thermal conductivity (0.05 W/m·K for perlite, 0.11 W/m·K for LECA). However, their compressive strength (6.35–13.97 MPa) is generally lower than that of pumice (8–12 MPa) or scoria (10–15 MPa), as noted by (Elhefny et al. 2025). This positions perlite and LECA as optimal choices for non-structural applications where thermal efficiency and weight reduction are prioritized over high mechanical strength.

From an engineering perspective, the comparison between Mix Design Type I (gravel-based, perlite as fine aggregate replacement) and Type II (LECA-based, perlite as fine aggregate replacement) reveals distinct application domains. Type I, with higher initial compressive strength (31.71 MPa at 0% perlite, decreasing to 6.35 MPa at 32.9% perlite, Table 7) and moderate density reduction (from 2.47 g/cm^3 to 1.61 g/cm^3), is well-suited for semi-structural applications, such as load-bearing partition walls, floor screeds, or precast elements requiring compressive strengths of 10–20 MPa. For instance, at 15.2% perlite replacement (Mix 5, Table 7), Type I achieves a compressive strength of 11.62 MPa and a specific gravity of 1.92 g/cm^3, ideal for semi-structural components balancing weight and strength. Conversely, Type II, with LECA as the coarse aggregate, achieves a significantly lower density (from 1.83 g/cm^3 to 0.90 g/cm^3) but reduced compressive strength (from 13.97 MPa to 6.62 MPa, Table 9). This makes Type II particularly suitable for ultra-lightweight applications, such as thermal insulation panels, lightweight fill systems, or non-load-bearing cladding, where thermal conductivity below 0.5 W/m·K and density below 1.0 g/cm^3 are critical.

For example, at 33.4% perlite replacement (Mix 9, Table 9), Type II achieves a specific gravity of 0.90 g/cm^3 and a thermal conductivity of 0.32 W/m·K, meeting stringent insulation requirements.

To guide practical implementation, safe replacement thresholds are proposed based on the experimental results and regression models:

Type I: Up to 20% perlite replacement is recommended for semi-structural applications to maintain compressive strength above 10 MPa (e.g., 11.62 MPa at 15.2% perlite, Table 7).

Type II: Up to 25% perlite with constant LECA content is suitable for insulation blocks, achieving thermal conductivity below 0.5 W/m·K and sufficient strength (e.g., 8.53 MPa at 18.1% perlite, Table 9).

Type IV: Maximum levels of 32.9% perlite and 44% LECA are ideal for ultra-light applications, such as prefabricated insulation panels, achieving density below 1.0 g/cm^3 and a minimum compressive strength of 5 MPa (Appendix A, Table 73).

These thresholds ensure a balance between performance and safety, tailored to specific application requirements. However, practical challenges include the higher cost of perlite (1.5–2 times that of conventional aggregates) and LECA (1.2–1.5 times), as well as their limited availability in some regions. These can be mitigated by optimizing mix ratios, sourcing local lightweight aggregates, or scaling production to reduce costs. Additionally, the reduced durability of high-aggregate mixes in harsh environments, such as coastal areas or regions with frequent freeze–thaw cycles, necessitates protective measures, such as epoxy coatings or confinement to indoor applications, to enhance serviceability.

Future research should focus on incorporating durability-enhancing additives (e.g., nano-silica, microfibers), exploring hybrid aggregate combinations, and conducting long-term durability tests under real-world conditions to validate and extend these findings. The statistical models and experimental framework established in this study provide a robust foundation for advancing sustainable, energy-efficient construction practices, enabling the design of lightweight concrete systems that optimize performance while minimizing environmental impact.

13 Conclusion

This study systematically investigated the performance of lightweight concrete incorporating perlite and lightweight expanded clay aggregate (LECA) across four mixture designs (Types I to IV) for non-structural applications. The key findings demonstrate the potential of these materials to advance sustainable construction, while also identifying critical limitations and practical recommendations for their implementation.

1. **Reduction in density and strength**: Increasing perlite and LECA content significantly reduced specific gravity (from 2.47 g/cm^3 to 0.90 g/cm^3) and compressive strength (from 31.59 MPa to 6.35 MPa). This trade-off makes these mixes highly suitable for non-structural applications where low density is prioritized, but it limits their use in load-bearing scenarios.
2. **Thermal insulation performance**: The mixes achieved thermal conductivity values as low as 0.32 W/m·K, meeting ASTM C177 requirements (0.3–0.5 W/m·K) for insulation panels and partition walls, thereby enhancing energy efficiency in buildings.
3. **Predictive models**: Strong linear relationships (R^2 up to 0.9996, p-values $<$ 0.01) were established between replacement levels of perlite and LECA and key concrete properties (compressive strength, tensile strength, density, and thermal conductivity). These models provide engineers with reliable tools for precise mix design optimization tailored to specific project requirements.
4. **Practical recommendations**: To maximize the benefits of perlite and LECA, engineers should adhere to safe replacement thresholds: up to 20% perlite and 10% LECA for semi-structural applications (e.g., partition walls requiring 10–15 MPa compressive strength); up to 25% perlite and 20% LECA for insulation blocks (thermal conductivity $<$ 0.5 W/m·K); and maximum levels of 32.9% perlite and 44% LECA for ultra-lightweight applications like prefabricated insulation panels or lightweight fill systems (density $<$ 1.0 g/cm^3, minimum 5 MPa strength). To address workability challenges, pre-soaking aggregates to saturated surface-dry (SSD) conditions and using polycarboxylate ether (PCE) superplasticizers (0.5–1.2% by cement weight) are recommended to maintain a consistent 2.5 cm slump. For cost optimization, locally sourced lightweight aggregates or alternatives like pumice should be considered to reduce material costs (1.5–2 times for perlite, 1.2–1.5 times for LECA compared to conventional aggregates).
5. **Engineering applications**: Type I mixes (gravel-based, up to 20% perlite) are recommended for semi-structural elements such as load-bearing partition walls, floor screeds, and precast panels, offering compressive strengths of 10–20 MPa and moderate density reduction

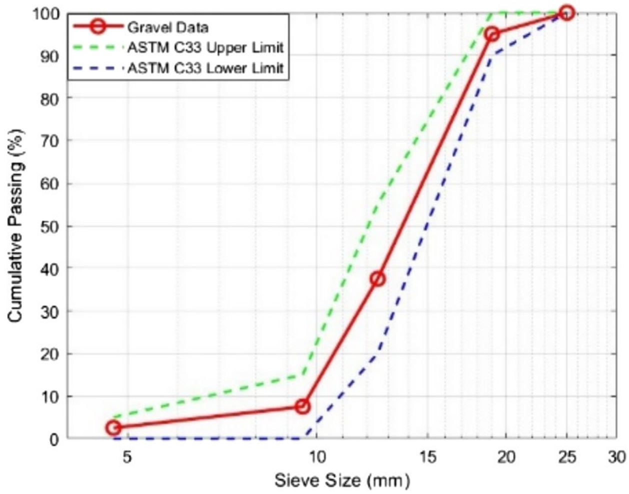

Fig. 36 Particle size distribution curve of the gravel used per (ASTM C33/C33M-18 2023)

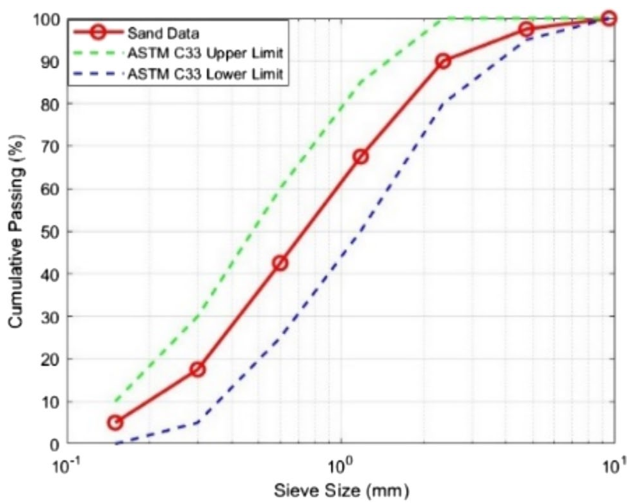

Fig. 37 Particle size distribution curve of the sand used per (ASTM C33/C33M-18 2023)

(1.61–2.47 g/cm^3). Type II–IV mixes, with higher LECA and perlite content, are ideal for ultra-light insulation applications, including thermal insulation panels, non-load-bearing cladding, and lightweight fill systems, achieving density as low as 0.90 g/cm^3 and thermal conductivity of 0.32–0.5 W/m·K. These applications align with sustainable construction goals, reducing transportation costs by 20–25% and CO_2 emissions by 10–12% compared to traditional concrete.

6. **Limitations**: The high porosity of perlite (25% water absorption) and LECA (19% water absorption) leads to reduced durability, particularly in harsh environments. Freeze–thaw resistance is a significant concern, with relative dynamic modulus (RDM) dropping from 92 to 70% in high-aggregate mixes (Tables 25 and 27), making these mixes unsuitable for cold climates with frequent freeze–thaw cycles. Similarly, reduced electrical resistivity increases the risk of reinforcement corrosion in chloride-laden environments, such as coastal areas. Sulfate exposure also poses challenges, as high porosity exacerbates sulfate attack, potentially compromising long-term durability. To mitigate these limitations, the use of durability-enhancing additives (e.g., nanosilica or microfibers), protective coatings (e.g., epoxy), or restricting applications to indoor environments is strongly recommended.

This study contributes a regression-based framework for designing perlite–LECA lightweight concrete, enabling engineers to optimize mix designs for specific non-structural applications while balancing mechanical performance, thermal efficiency, and sustainability.

Table 34 Physical properties of Ardabil Pozzolanic Portland Cement per (ASTM C618-25a 2025)

Pozzolanic	Fineness	Setting Time		Compressive Strength kg/cm^2			Soundness
	Blain cm^2/gr	INIT (Min)	Final (Min)	3 Days	7 Days	28 Days	Auto Clave (%)
Ardabil cement	3617 ± 274	139 ± 15	181 ± 22	183 ± 16	256 ± 17	361 ± 21	0.0.2 ± 0.12
ISIRI 3432	> 3000	> 60	< 420	> 100	> 175	> 300	> – 0.2 & < 0.8

Table 35 Chemical properties of Ardabil Pozzolanic Portland Cement per (ASTM C618-25a 2025)

Pozzolanic	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CI	Loss
Ardabil Cement	19.49 ± 0.62	4.84 ± 0.38	3.00 ± 0.23	52.65 ± 1.30	2.23 ± 0.27	2.37 ± 0.13	0.01	3.02 ± 0.23
ISIRI 3432	–	–	–	–	< 6	< 4	< 0.1	< 5

Appendix A: Raw Material and Test Result Details

(See Figs. 36, 37 and Tables 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 7)

Table 36 Particle size distribution of aggregates used per ASTM C33 (ASTM C33/C33M-18 2023)

Sieve size	Opening (mm)	Percent passing (gravel)	Percent passing (sand)
3.4	19	100.00	100.00
1.2	12.5	91.10	100.00
3.8	9.50	67.12	100.00
4	4.75	4.36	99.97
8	2.36	0.43	92.96
16	1.18	0.00	77.35
30	0.60	0.00	58.00
50	0.30	0.00	22.32

Table 37 Particle size distribution and usage percentage of perlite

Perlite type	Particle size range (mm)	Percentage used (%)
R_1	0–0.15	20
R_2	0.15–0.5	0
R_3	0.5–1.0	20
R_4	1.0–2.5	60

Table 38 Physical and thermal properties of perlite

Property	Value
Luster	Vitreous
Texture	Vitreous
Chemical composition	Aluminum silicate (transforms to kaolinite, zeolite and montmorillonite under weathering)
Water content	3.5%
Expansion temperature	950 °C
Expanded volume	15 times the original volume
Melting point	1300 °C
Hardness	6 (Mohs scale), brittle with high friability
Thermal conductivity	0.05 W/m·K
pH	7.2
Flammability	Non-flammable
Refractive Index	1.50
Maximum free moisture	0.4%
Density	873 kg/m^3

Table 39 Chemical composition of perlite used

Component	Weight percentage (%)
Silicon dioxide (SiO_2)	72.5
Aluminum oxide (Al_2O_3)	13.5
Sodium oxide (Na_2O)	3.8
Potassium oxide (K_2O)	4.2
Iron oxide (Fe_2O_3)	1.0
Magnesium oxide (MgO)	0.5
Calcium oxide (CaO)	1.0
Water (H_2O)	4.0

Author Contributions Houshyar Eimani kalehsar conceptualization,

Table 40 Physical properties of Leca aggregates

Property	Value
Bulk density	650 kg/m^3
Particle size range	4–10 mm
Water absorption (24 h)	19%
Compressive strength (single particle)	2.5 MPa
Thermal conductivity	0.110 W/m·K

Table 41 Chemical composition of Leca aggregates

Chemical component	SiO_2	Al_2O_3	Fe_2O_3	CaO
Range (%)	62.5	18.0	7.5	2.0

Table 42 Test results of mix design 1 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	30.2	9.3	–	18	0.57	2.5	2.47	28.93
2	42.5	30.2	9.3	–	18	0.57	2.5	2.47	31.19
3	42.5	30.2	9.3	–	18	0.57	2.5	2.47	33.34
4	42.5	30.2	9.3	–	18	0.57	2.5	2.47	30.89
5	42.5	30.2	9.3	–	18	0.57	2.5	2.47	32.85
6	42.5	30.2	9.3	–	18	0.57	2.5	2.47	32.46
Mean								**2.47**	**31.60**

Table 43 Test results of mix design 2 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	21.77
2	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	21.38
3	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	22.25
4	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	24.52
5	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	23.05
6	42.5	26.9	9.3	3.8	17.5	0.56	2.5	2.28	21.38
Mean								**2.28**	**22.39**

Table 44 Test results of mix design 3 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	17.65
2	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	20.10
3	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	18.73
4	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	18.23
5	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	19.61
6	42.5	23.3	9.3	7.6	17.3	0.55	2.5	2.16	17.55
Mean								**2.16**	**18.65**

Table 45 Test results of mix design 4 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	16.18
2	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	13.24
3	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	13.73
4	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	15.30
5	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	14.51
6	42.5	19.9	9.3	11.4	17	0.54	2.5	2.04	15.59
Mean								**2.04**	**14.76**

Table 46 Test results of mix design 5 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.18
2	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.77
3	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.08
4	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	12.26
5	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.57
6	42.5	16.2	9.3	15.2	16.8	0.53	2.5	1.92	11.87
Mean								**1.92**	**11.62**

Table 47 Test results of mix design 6 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	9.32
2	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	10.40
3	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	8.73
4	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	9.02
5	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	8.63
6	42.5	13.3	9.3	19	15.9	0.5	2.5	1.86	8.83
Mean								**1.86**	**9.15**

Table 48 Test results of mix design 7 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	7.85
2	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	7.45
3	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	7.35
4	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	8.24
5	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	6.86
6	42.5	9.8	9.3	22.8	15.7	0.49	2.5	1.81	7.75
Mean								**1.81**	**7.58**

Table 49 Test results of mix design 8 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	6.57
2	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	6.86
3	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	7.26
4	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	6.67
5	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	7.45
6	42.5	6.1	9.3	26.6	15.5	0.49	2.5	1.76	6.96
Mean								**1.76**	**6.96**

Table 50 Test results of mix design 9 Type I (28 days)

Mix no.	Gravel (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.47
2	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.28
3	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.47
4	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	5.98
5	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.77
6	42.5	–	9.3	32.9	15.3	0.48	2.5	1.61	6.18
Mean								**1.61**	**6.35**

Table 51 Test results for mix design 1 Type II (28 days)

Mix no.	Lecan (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	14.22
2	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	13.54
3	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	13.34
4	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	14.71
5	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	14.42
6	42.5	31.7	9.3	0.0	16.5	0.55	2.5	1.83	13.63
Mean								**1.83**	**13.97**

Table 52 Test results for mix design 2 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	12.26
2	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	12.94
3	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	12.75
4	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	12.55
5	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	11.77
6	42.5	27.7	9.3	4.2	16.3	0.55	2.5	1.68	12.06
Mean								**1.68**	**12.38**

Table 53 Test results for mix design 3 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.76
2	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.27
3	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.57
4	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.18
5	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	10.98
6	42.5	23.3	9.3	8.9	16.0	0.54	2.5	1.62	11.47
Mean								**1.62**	**11.37**

Table 54 Test results for mix design 4 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	10.59
2	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	10.00
3	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	9.02
4	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	9.61
5	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	10.39
6	42.5	18.9	9.3	13.5	15.8	0.53	2.5	1.38	9.80
Mean								**1.38**	**9.90**

Table 55 Test results for mix design 5 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	8.72
2	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	9.12
3	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	7.74
4	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	8.23
5	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	8.53
6	42.5	14.5	9.3	18.1	15.6	0.53	2.5	1.26	8.82
Mean								**1.26**	**8.53**

Table 56 Test results for mix design 6 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	6.76
2	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.64
3	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.06
4	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.45
5	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.06
6	42.5	10.1	9.3	22.7	15.4	0.52	2.5	1.16	7.25
Mean								**1.16**	**7.20**

Table 57 Test results for mix design 7 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.76
2	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.66
3	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.66
4	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.86
5	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.27
6	42.5	5.7	9.3	27.3	15.2	0.52	2.5	1.06	6.37
Mean								**1.06**	**6.59**

Table 58 Test results for mix design 8 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.37
2	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.66
3	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.76
4	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.37
5	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.86
6	42.5	1.3	9.3	31.9	15.0	0.51	2.5	1.00	6.96
Mean								**1.00**	**6.66**

Table 59 Test results for mix design 9 Type II (28 days)

Mix no.	Leca (%)	Sand (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.57
2	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.86
3	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.27
4	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.66
5	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.47
6	42.5	0.0	9.3	33.4	14.8	0.50	2.5	0.90	6.96
Mean								**0.90**	**6.62**

Table 60 Test results for mix design 1 Type III (28 Days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	28.93
2	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	31.18
3	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	33.34
4	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	30.89
5	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	32.85
6	42.5	0.0	30.2	9.3	18.0	0.61	2.5	2.47	32.46
Mean								**2.47**	**31.59**

Table 61 Test results for mix design 2 Type III (28 Days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	28.93
2	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	29.71
3	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	27.65
4	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	28.73
5	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	28.34
6	35.7	7.0	30.2	9.3	17.8	0.61	2.5	2.35	29.12
Mean								**2.35**	**28.75**

Table 62 Test results for mix design 3 Type III (28 days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	27.75
2	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	27.06
3	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	26.38
4	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	26.77
5	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	27.36
6	28.9	14.0	30.2	9.3	17.6	0.60	2.5	2.23	26.57
Mean								**2.23**	**26.99**

Table 63 Test results for mix design 4 Type III (28 days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	25.30
2	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	24.41
3	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	25.98
4	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	25.59
5	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	24.81
6	22.2	21.0	30.2	9.3	17.3	0.59	2.5	2.17	25.39
Mean								**2.17**	**25.25**

Table 64 Test results for mix design 5 Type III (28 days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	23.34
2	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	22.06
3	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	22.55
4	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	21.67
5	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	21.37
6	15.5	28.0	30.2	9.3	17.0	0.58	2.5	2.06	23.43
Mean								**2.06**	**22.40**

Table 65 Test results for mix design 6 Type III (28 Days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	18.92
2	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	20.59
3	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	19.41
4	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	18.53
5	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	20.00
6	8.7	35.0	30.2	9.3	16.8	0.57	2.5	1.90	19.02
Mean								**1.90**	**19.41**

Table 66 Test results for mix design 7 Type III (28 days)

Mix no.	Gravel (%)	Leca (%)	Sand (%)	Cement (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	16.18
2	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	17.45
3	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	16.27
4	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	14.71
5	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	15.39
6	0.0	44.0	30.2	9.3	16.5	0.56	2.5	1.83	16.57
Mean								**1.83**	**16.09**

Table 67 Test results for mix design 1 Type IV (28 Days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific Gravity (g/cm^3)	Compressive Strength (MPa)
1	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	7.75
2	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	7.26
3	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	6.47
4	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	7.94
5	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	6.77
6	42.5	0.0	9.3	32.9	15.4	0.52	2.5	1.61	7.16
Mean								**1.61**	**7.23**

Table 68 Test results for mix design 2 Type IV (28 days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	7.45
2	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.96
3	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.47
4	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.67
5	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.77
6	35.7	7.0	9.3	32.9	15.3	0.51	2.5	1.50	6.18
Mean								**1.50**	**6.75**

Table 69 Test results for mix design 3 Type IV (28 days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific Gravity (g/cm^3)	Compressive Strength (MPa)
1	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.37
2	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.67
3	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.86
4	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.96
5	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	6.77
6	28.9	14.0	9.3	32.9	15.2	0.51	2.5	1.41	7.16
Mean								**1.41**	**6.80**

Table 70 Test results for mix design 4 Type IV (28 days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.47
2	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.28
3	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.47
4	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	5.98
5	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.77
6	22.2	21.0	9.3	32.9	15.1	0.50	2.5	1.34	6.18
Mean								**1.34**	**6.35**

Table 71 Test results for mix design 5 Type IV (28 Days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific Gravity (g/cm^3)	Compressive Strength (MPa)
1	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	5.30
2	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	6.28
3	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	5.49
4	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	5.98
5	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	5.79
6	15.5	28.0	9.3	32.9	15.0	0.50	2.5	1.26	6.18
Mean								**1.26**	**5.84**

Table 72 Test results for mix design 6 Type IV (28 days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	5.88
2	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	5.30
3	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	5.49
4	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	5.98
5	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	4.81
6	8.7	35.0	9.3	32.9	14.9	0.49	2.5	1.16	6.18
Mean								**1.16**	**5.61**

Table 73 Test results for mix design 7 Type IV (28 days)

Mix no.	Gravel (%)	Leca (%)	Cement (%)	Perlite (%)	Water (%)	W/C	Slump (cm)	Specific gravity (g/cm^3)	Compressive strength (MPa)
1	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	5.88
2	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	6.28
3	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	5.49
4	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	5.98
5	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	5.79
6	0.0	43.0	9.3	32.9	14.8	0.49	2.5	1.00	6.18
Mean								**1.00**	**5.93**

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