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Investigation of the Effects of Water-to-Cement Ratios on Concrete with Varying Fine Expanded Perlite Aggregate Content

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Abstract

This study investigates the influence of varying water-to-cement (W/C) ratios and fine aggregate compositions on the performance of concrete incorporating expanded perlite aggregate (EPA) as a lightweight alternative to natural sand. A total of eighteen concrete mixes were produced, each with different W/C ratios and fine-to-coarse aggregate (FA/CA) ratios, and evaluated for workability, compressive strength, flexural and tensile strength, water absorption, density, and thermal conductivity. Perlite was used to fully replace natural sand in half of the mixes, allowing a direct assessment of its effects across low-, medium-, and high-strength concrete formulations. The results demonstrate that EPA can improve workability and reduce both density and thermal conductivity, with variable impacts on mechanical performance depending on the W/C and FA/CA ratios. Notably, higher cement contents enhanced the internal curing effect of perlite, while lower-strength mixes experienced a reduction in compressive strength when perlite was used. These findings suggest that expanded perlite can be effectively applied in structural and non-structural concrete with optimized mix designs, supporting the development of lightweight, thermally efficient concretes. Mixture W16-100%EPS was considered the ideal mix because its compressive strength at the age of 65 days 44.2 MPa and the reduction in compressive strength compared to the reference mix 14% and the reduction in density 5.4% compared with the reference mix and the reduction in thermal conductivity 14% compared with the reference mix.

Keywords: self-curing mechanism; lightweight concrete; expanded perlite aggregate; fine aggregate replacement; thermal performance; mechanical properties

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1. Introduction

Producing lightweight concrete is advantageous due to its ability to reduce dead loads and minimize stress on structural foundations. However, the techniques commonly employed in manufacturing lightweight concrete often lead to a reduction in compressive strength and other structural performance characteristics. Lightweight aggregates such as perlite have gained attention due to their ability to reduce concrete density while improving thermal insulation. It has been demonstrated that high-performance lightweight concrete can achieve 28-day compressive strengths of up to 50 MPa when natural perlite aggregate is used [1].

There are various types of lightweight perlite aggregate, including both coarse and fine grades. Perlite aggregate, due to its high porosity and low bulk density, is particularly suited for lightweight concrete applications. Generally, an increase in the proportion of perlite in the mix results in a reduction in compressive strength [2]. The slump of concrete increases slightly—by around 10 mm—as the perlite content rises, and a reduction in compressive strength of approximately 40% was observed when fine aggregate was fully replaced by perlite at a water-to-cement (W/C) ratio of 0.38 [3].

Aggregates with high water absorption, such as perlite, can act as internal curing agents, providing moisture for ongoing hydration after initial setting. Notably, all existing research identifies perlite aggregate as having a high water absorption capacity [4]. This internal curing ability makes perlite beneficial for enhancing the hydration process in low water-to-cement ratio mixes. Increasing the dosage of expanded perlite aggregate (EPA) in concrete greatly enhances its thermal efficiency; thermal conductivity can be reduced by up to 60%, depending on the amount of EPA used [5].

Jedidi et al. [6] conducted a study investigating the effects of substituting sand with lightweight perlite aggregate at replacement levels from 0% to 80%. With a cement-to-water ratio of 0.7, results indicated a decline in compressive strength, and the concrete's density varied between 560 kg/m^3 and 1510 kg/m^3.

High-strength and lightweight concrete can be produced simultaneously, with compressive strengths in the range of 58–62 MPa, by using lightweight aggregates such as sinospheric or expanded clay aggregate [7]. This type of concrete enhances structural efficiency, reduces seismic inertial forces, and allows for greater load-bearing capacity and span length [8]. The primary method for reducing concrete weight involves replacing dense natural aggregates with lightweight alternatives, typically followed by the use of porous materials characterized by extremely low densities [9]. Another approach for producing lightweight concrete is to introduce a high volume of air voids, which can be achieved through the use of chemically generated gases or physically stabilized foaming agents [10].

Despite its advantages, ultra-high-performance concrete suffers from significant autogenous shrinkage due to its high fine powder content and low water-to-cement ratio—one of its main limitations [11]. To mitigate this issue and reduce the likelihood of early-age cracking, numerous strategies have been proposed, such as the use of self-curing agents, shrinkage-reducing admixtures, fibers, and expansive agents [12–18]. Achieving both high strength and reduced weight in concrete can also be accomplished by replacing conventional aggregates with strong lightweight alternatives and partially substituting cement with pozzolanic materials, such as fly ash, silica fume, metakaolin, and ground granulated blast furnace slag [19–23].

Another effective method for enhancing the performance of lightweight concrete is the inclusion of reinforcing fibers, such as iron, carbon, and others [24,25]. Domagała and Bryła [26] examined the effects of pre-coating lightweight aggregates with cement paste, finding that this technique significantly improved the properties of concrete. The pre-coated aggregates led to a density increase of up to 19%, a strength gain of up to 107%, and a reduction in water absorption by as much as 52%. Aslam et al. [27] utilized oil-palm-boiler clinker (OPBC), a waste product from the palm oil industry, as a lightweight aggregate, introducing it into the mix at replacement levels of 20%, 40%, and 60% by volume. Their results demonstrated that substituting 20–40% of natural aggregates with OPBC successfully transformed high-strength semi-lightweight concrete into high-strength lightweight concrete. Hosen et al. [28] explored the ductility performance of lightweight, high-strength concrete enhanced with steel fibers. In their study, steel-fiber-reinforced concrete incorporating palm oil clinker (POC) was developed and evaluated for ductility characteristics. POC was employed as both a supplementary cementitious material and a lightweight aggregate, while steel fibers were added in volumes ranging from 0% to 1.50%, in 0.5% increments. Compared to the control mixes (without steel fibers), the enhanced specimens showed increases of up to 472% in compression ductility, 140% in displacement ductility, and 568% in energy ductility.

Sengul et al. [29] employed lightweight perlite aggregate to manufacture lightweight concrete. The perlite used had a bulk density of 54 kg/m^3 and a water absorption rate of 310%. Six concrete mixes were prepared, each with varying percentages of perlite aggregate alongside natural sand, using a water-to-cement ratio of 0.55. The perlite aggregate was pre-soaked prior to mixing. The results indicated that substituting conventional aggregate with expanded perlite significantly reduced the thermal conductivity of the concrete mixtures. However, as the expanded perlite content increased, both the compressive strength and modulus of elasticity declined. Higher concentrations of perlite also led to increased water absorption and sorptivity. Despite this, lightweight perlite aggregate remains an effective material for producing lightweight concrete [30]. Its high water absorption capacity makes expanded perlite beneficial for internal curing, supplying moisture for ongoing cement hydration [31]. Lightweight aggregates offer favorable thermal conductivity and contribute to the thermal insulation properties of concrete [32].

Pramusanto et al. [33] studied lightweight concrete made with 100% expanded perlite as the primary aggregate and 50% natural sand by volume, adjusting the total aggregate volume between 80% and 89%. Their findings confirmed that increased use of expanded perlite substantially reduced the density of concrete, although compressive strength declined with higher perlite content. Othman et al. [34] replaced coarse aggregate with lightweight LECA in four mixes and substituted sand with expanded perlite in seven additional mixes. A mixture containing 60% LECA and 50% EPA was identified as optimal, achieving a D1.8 lightweight classification, meeting the minimum compressive strength requirements and qualifying as high-quality concrete.

Other studies have involved treating lightweight aggregates with silica fume solutions at varying concentrations, which has been shown to enhance the structural performance of the resulting concrete [35]. While the early-age (7-day) compressive strength of lightweight concrete incorporating silica fume shows little improvement, it increases significantly by 28 days due to prolonged curing effects [36]. Expanded perlite typically has a bulk density of 60 to 80 kg/m^3, in contrast to conventional mineral aggregates, which range between 1520 and 1680 kg/m^3 [37]. As the proportion of perlite increases, the compressive strength and modulus of elasticity of concrete decrease, although the reduction in elasticity is generally more pronounced than the reduction in strength. It is also noteworthy that higher perlite content contributes to increased concrete slump [3].

Tapan and Engin [38] produced ultra-lightweight concrete using expanded perlite aggregates of varying particle sizes, including 1.1 mm, <300 microns, 2 mm, and 3.6 mm. They observed that larger perlite particles led to lower concrete density, whereas smaller sizes increased it. All mixtures had densities below 450 kg/m^3, and their compressive strengths ranged between 0.1 and 1.2 MPa. Jedidi et al. [6] replaced sand with lightweight perlite aggregate in proportions ranging from 0% to 80% by volume, using 300 kg/m^3 of cement, and found that concrete density varied from 560 to 1710 kg/m^3, with compressive strength ranging from 3.4 to 30 MPa and thermal conductivity between 0.13 and 0.62 W/m·K, indicating that increasing the lightweight aggregate content leads to improved thermal insulation.

In recent years, numerous studies have explored the use of recycled and waste-derived materials—such as expanded polystyrene beads, rubber particles, crushed glass, and recycled plastic waste—as lightweight aggregates to enhance sustainability and reduce construction waste [39,40]. These materials often offer low density and reduced thermal conductivity, contributing to energy-efficient concrete systems. However, many of them present challenges such as poor bond strength, inconsistent particle geometry, or incompatibility with the cement matrix without surface treatment. Compared to these alternatives, expanded perlite offers a unique combination of properties: high porosity and water absorption for internal curing, thermal insulation, stable mineral composition, and better compatibility with cementitious materials. In this study, expanded perlite is used not only for its insulating potential but also for its ability to contribute to strength retention via internal moisture release, especially at lower W/C ratios. While the environmental footprint of perlite is not zero, its lightweight and self-curing characteristics offer distinct advantages in lightweight structural and thermally efficient concrete design.

This research addresses the challenge of balancing low density and mechanical performance in lightweight concrete by investigating the influence of expanded perlite aggregate (EPA) under varying water-to-cement (W/C) and fine-to-coarse aggregate (FA/CA) ratios. While several lightweight aggregates—such as expanded clay, pumice, and sintered fly ash—have been extensively studied, expanded perlite remains underexplored, particularly in terms of how it interacts with different W/C and FA/CA ratios. Compared to expanded clay and pumice, expanded perlite offers superior thermal insulation and lower density, but tends to have lower strength and higher water absorption. Despite its promising characteristics for thermal performance, limited research has investigated how varying mix parameters affect its mechanical behavior. Therefore, this study aims to fill that gap by systematically evaluating the combined effects of W/C and FA/CA ratios on the structural and thermal properties of concrete made with 100% replacement of natural sand by expanded perlite.

2. Materials

In this study, sulfate-resistant Portland cement, conforming to the Iraqi Standard Specification (IQS No. 5) [41], was utilized. The chemical composition and physical properties of the cement are provided in Table 1. Natural coarse aggregate with a maximum size of 20 mm and natural river sand with a maximum particle size of 4.75 mm were used. Both aggregates met the requirements of IQS No. 45 [42]. The chemical and physical characteristics of the coarse and fine aggregates are detailed in Table 2.

Table 1. Physical and chemical properties of cement.

Ingredients	Percentages, %	Physical Properties	Value
CaO	63.4	Initial setting time, Min	130
SiO_2	20.2	Final setting time, Hr	4
Al_2O_3	4.5	2-day compressive strength, MPa	15
Fe_2O_3	6.3	28-day compressive strength, MPa	27
SO_3	2.48		
MgO	1.88		

The lightweight aggregate employed was expanded perlite, used as a fine aggregate with a maximum size of 3 mm, a dry bulk density of 80 kg/m^3, and a water absorption capacity of 136%. The perlite was sourced from Akper Perlite Ltd., Cankiri, Turkey, and complies with ASTM C332 for lightweight aggregates used in insulating concrete. Its origin and production process are important, as the physical properties of expanded perlite can vary depending on the raw material and expansion method used. Sieve analysis of perlite was performed according to Othman et al. [34], and the results are presented in

Table 3. The perlite was placed in a cloth and soaked in water for two minutes, then left for 24 h to dry and then used by mixing. To prevent uncontrolled absorption of mixing water, the expanded perlite aggregate was pre-soaked in water for 24 h and then brought to a saturated surface-dry (SSD) condition before use. This ensured that its pores were internally saturated while the surface remained dry, preventing it from absorbing additional water during mixing. As a result, the water-to-cement (W/C) ratios reported in this study accurately represent the effective free water available for cement hydration, and no correction for aggregate absorption was necessary.

Table 2. Physical and chemical properties of the aggregates.

Property	Aggregate Type	
	Coarse Aggregate	Fine Aggregate
Specific gravity	2.61	2.6
Density, kg/m^3	1620	1580
Water absorption, %	0.21	0.8
SO_3, %	0	0.2

Table 3. Sieve analysis of fine perlite aggregate.

Sieve Size, mm	Passing, %
10	0
4.75	0
2.36	76.9
1.18	21.4
0.6	5.17
0.3	4.91
0.15	0

The physical properties of the cement and coarse aggregate listed in Tables 1 and 2 were obtained from supplier datasheets. The water absorption and dry bulk density of the expanded perlite were determined in the laboratory according to ASTM C128. The chemical composition of the cement shown in Table 3 was provided by the manufacturer and corresponds to a typical Type I Portland cement.

The silica fume used in the mixes contained 93% SiO_2 and 4.2% CaO, and was added at a dosage of 10% relative to the cement weight. Silica fume was incorporated to improve the strength and durability of the concrete. Due to its ultrafine particle size and high pozzolanic reactivity, silica fume fills voids between cement grains and reacts with calcium hydroxide to form additional calcium silicate hydrate (C–S–H), which enhances both the compressive strength and impermeability of the concrete matrix. Figure 1 illustrates the materials used in this research.

(a) (b) (c)

Figure 1. Materials used: (**a**) coarse aggregate, (**b**) silica fume, and (**c**) perlite aggregate.

3. Mix Proportion and Casting

In this study, a total of 18 concrete mixes were prepared using various W/C ratios of 0.4, 0.31, 0.25, and 0.2. Additionally, different coarse-to-fine aggregate (CA/FA) ratios were employed to increase the proportion of fine aggregate. The normal concrete was designed according to ACI 211.1-91 [43]. Some mixes were produced without lightweight perlite aggregate, while others were made by fully replacing the fine aggregate with lightweight perlite aggregate (PA) on a volumetric basis, as shown in Table 4. As the W/C ratio was varied while keeping water content constant across some groups, cement dosage ranged from 381 to 760 kg/m^3 depending on the mix. This variation is reflected in the mix design table and should be considered when interpreting strength results. For clarity, mix codes were renamed to reflect key parameters: the water-to-cement ratio (W/C), the fine-to-coarse aggregate ratio (FA/CA), and the use of expanded perlite (EPA). For example, W31-FA1.6-EPA refers to a mix with a W/C ratio of 0.31, FA/CA ratio of 1.6, and 100% EPA as fine aggregate. Silica fume (SF) was added to all mixes at a dosage of 10% by weight of cement. In Table 4, HRWR stands for high-range water-reducing admixture (superplasticizer). All mixtures were prepared using an electrically driven laboratory mixer, which is illustrated in Figure 2. The compressive strength of the concrete was evaluated in accordance with the British Standard (BS EN 12390–4) [44] using 100 × 100 × 100 mm cubic molds, tested at three curing ages: 7, 28, and 65 days. Flexural strength testing was performed at 28 days following the American Standard (ASTM C78) [45], using prism specimens measuring 100 × 100 × 400 mm. The splitting tensile strength test was conducted at 28 days based on the American Standard (ASTM C496) [46], using cylindrical specimens with a diameter of 100 mm and a height of 200 mm. The oven dry concrete density and water absorption was performed according to ASTM C642 [47]. Figure 3 displays the procedures for compressive strength, tensile strength, and flexural strength testing.

Table 4. Concrete mix proportion.

Mixes	Mix Proportion	Materials, Kg/m^3								
		W/C	FA/CA	Cement	Water	SF	CA	FA	EPA	HRWR
W1-0%EPA *	1-2.37-1	0.31	2.38	490	169	55	490	1162	0	2.2
W2-0%EPS	1-1.83-1.5	0.31	1.22	490	169	55	735	899	0	2.1
W3-0% EPA	1-1.37-2	0.31	0.68	490	169	55	980	672	0	2.1
W4-100% EPA	1-2.37-1	0.31	2.38	490	169	55	490	0	144	1.1
W5-100% EPA	1-1.83-1.5	0.31	1.22	490	169	55	735	0	113	0
W6-100% EPA	1-1.37-2	0.31	0.68	490	169	55	980	0	93	0.4
W7-0% EPA	1-3.6-1	0.4	3.57	381	169	42	381	1376	0	1.33
W8-0% EPA	1-3.1-1.5	0.4	2.08	381	169	42	572	1185	0	1.9
W9-0% EPA	1-2.61-2	0.4	1.30	381	169	42	762	995	0	3
W10-100% EPA	1-3.6-1	0.4	3.57	381	169	42	381	0	280	0
W11-100% EPA	1-3.1-1.5	0.4	2.08	381	169	42	572	0	239	0
W12-100% EPA	1-2.61-2	0.4	1.30	381	169	42	762	0	165	0
W13-0% EPA	1:0.28:1.36	0.2	0.21	760	169	85	1152	242	0	9.2
W14-100% EPA	1:0.28:1.36	0.2	0.21	760	169	85	1152	0	55	9.2
W 15-0% EPA	1:0.5:1.7	0.25	0.34	608	169	68	1152	388	0	5.5
W 16-100% EPA	1:0.5:1.7	0.25	0.34	608	169	68	1152	0	101	1.1
W 17-0% EPA	1:1.1:2.5	0.31	0.43	490	169	55	1152	500	0	1.36
W 18-100% EPA	1:1.1:2.5	0.31	0.43	490	169	55	1152	0	122	0

* EPA: Perlite aggregate.

Figure 2. Mixing concrete with an electrically driven laboratory mixer.

(**a**) (**b**) (**c**)

Figure 3. Tests performed: (**a**) flexural strength, (**b**) tensile strength, and (**c**) compressive strength.

The selected water-to-cement (W/C) ratios—0.2, 0.25, 0.31, and 0.4—were chosen to represent a broad range of practical concrete applications, from high-performance concrete (low W/C) to conventional structural concrete (higher W/C). This variation allows for the evaluation of how perlite aggregate behaves under different hydration and strength development conditions. Similarly, the fine-to-coarse aggregate (FA/CA) ratios were adjusted to simulate varying aggregate packing conditions and surface area demands, which influence concrete workability, density, and internal curing potential. These ratios reflect realistic mix design scenarios encountered in structural and non-structural applications.

4. Experimental Results and Discussion

This section presents and analyzes the test results of all 18 concrete mixes in terms of slump, compressive strength, flexural strength, tensile strength, density, water absorption, and thermal conductivity. Key trends include an increase in workability (slump) with the use of expanded perlite, particularly due to its high water absorption and pre-wetted condition. Compressive, flexural, and tensile strengths were generally maintained or moderately reduced in mixes with adequate cement content, though more significant losses occurred in high-strength mixes. Perlite use resulted in lower density and thermal conductivity, indicating suitability for lightweight and thermally efficient concrete. Water absorption increased with perlite content, especially in lower cement mixes, but was partially offset by internal curing in mixes with lower W/C ratios.

For each test, three replicate specimens were prepared and measured. The average values are reported, and standard deviations are represented by error bars in the figures where applicable.

4.1. Slump Test

The concrete slump test was performed in accordance with the American Standard (ASTM C143) [48]. The results of the slump test were influenced by the W/C ratio. When the W/C ratio was 0.31 without perlite aggregate, the slump ranged from 6.5 to 10 cm, whereas with the addition of perlite aggregate, the slump increased to 12–19 cm. At a W/C ratio of 0.4 without perlite, the slump was 10–22 cm, and with perlite, it increased slightly to 22–23 cm. For the mix with a W/C ratio of 0.2, the slump was 18 cm without perlite, increasing to 25 cm with perlite. A similar trend was observed in the remaining mixtures, confirming that the use of the expanded perlite aggregate contributes to increased slump values. This is attributed to the fact that the perlite aggregate was pre-wetted a day prior to mixing, and due to its high water absorption capacity, it retained moisture, thereby improving the workability (slump) of the concrete mixture. Table 5 presents the slump values for all mixes, and Figure 4 illustrates the slump test procedure.

Table 5. Slump for all mixes.

Mixes	Slump, cm	Mixes	Slump, cm
W1-0%EPA	10	W10-100% EPA	22
W2-0%EPS	10	W11-100% EPA	23
W3-0% EPA	6.5	W12-100% EPA	23
W4-100% EPA	19	W13-0% EPA	18
W5-100% EPA	10	W14-100% EPA	25
W6-100% EPA	12	W15-0% EPA	14
W7-0% EPA	10	W16-100% EPA	7
W8-0% EPA	11	W17-0% EPA	4
W9-0% EPA	22	W18-100% EPA	12

Figure 4. Slump test.

4.2. Compressive Strength

At a W/C ratio of 0.31 and a cement content of 490 kg/m^3, the compressive strength at 65 days for the initial mix (W1-0%EPA) was 18.65 MPa, which is nearly equivalent to that of mix W4-100% EPA (containing 100% perlite aggregate), which reached 18.8 MPa. This comparable performance can be attributed to the self-curing mechanism provided by the perlite aggregates, which helped sustain compressive strength. The same explanation applies to mixes W2-0%EPS, W5-100% EPA, W3-0% EPA, and W6-100% EPA. Based on the 65-day results, compressive strength was influenced by the FA/CA ratio, where a lower FA/CA ratio corresponded to a higher compressive strength, with an increase of up to 29% observed in mix W6-100% EPA.

The comparable or improved strength results observed in these mixes highlight the potential of expanded perlite as an internal curing agent. Its high absorption capacity and pre-wetted state allowed for a gradual release of moisture during hydration, effectively extending curing internally especially important in low W/C mixes where external curing is insufficient. This internal curing helps maintain hydration of cement particles, reduces early-age shrinkage, and refines pore structure, which collectively improves compressive strength. In these cases, the benefits of internal curing counterbalance the inherently lower strength of the lightweight aggregate.

At a W/C ratio of 0.4 and a cement content of 381 kg/m^3, compressive strength declined with the addition of perlite aggregate, primarily due to the reduced cement content, which limited the effectiveness of internal curing. For example, mix W7-0% EPA recorded a compressive strength of 12.2 MPa, while mix W10-100% EPA (with perlite) dropped to 6.9 MPa. A similar pattern was observed in mixes W8-0% EPA, W11-100% EPA, W9-0% EPA, and W12-100% EPA, all of which experienced reduced compressive strength when perlite was used. These mixes differed in coarse-to-fine aggregate ratios: W7-0% EPA and W10-100% EPA had a ratio of 0.27, W8-0% EPA and W11-100% EPA had a ratio of 0.76, and W9-0% EPA and W12-100% EPA had a ratio of 2.39.

For mixes with a W/C ratio of 0.2, the compressive strength at 65 days was 57 MPa for the mix without perlite (W13-0% EPA). When perlite aggregate was introduced in mix W14-100% EPA, the compressive strength decreased to 45 MPa, which is attributed to the inherent weakness and low density of the perlite aggregate. This reduction is more pronounced in high-strength concrete with high cement contents. In mixes W15-0% EPA and W 16-100% EPA, a W/C ratio of 0.25 and cement content of 608 kg/m^3 were used. Mix W16-100% EPA, which included perlite aggregate, exhibited lower compressive strength for similar reasons, reinforcing the trend of strength reduction in high-strength concrete incorporating lightweight aggregates.

Mixes W17-0% EPA and W18-100% EPA were produced with the same W/C ratio and cement content as mixes W1-0%EPA to W6-100% EPA, but with different mixing proportions, particularly a coarse-to-fine aggregate ratio of 2.3. The addition of perlite in mix W18-100% EPA once again resulted in a decrease in compressive strength. Figure 5 illustrates the compressive strength over time for mixes without perlite aggregate, while Figure 6 shows the same for mixes containing perlite. Figure 7 presents compressive strength values at 65 days in relation to the W/C ratio.

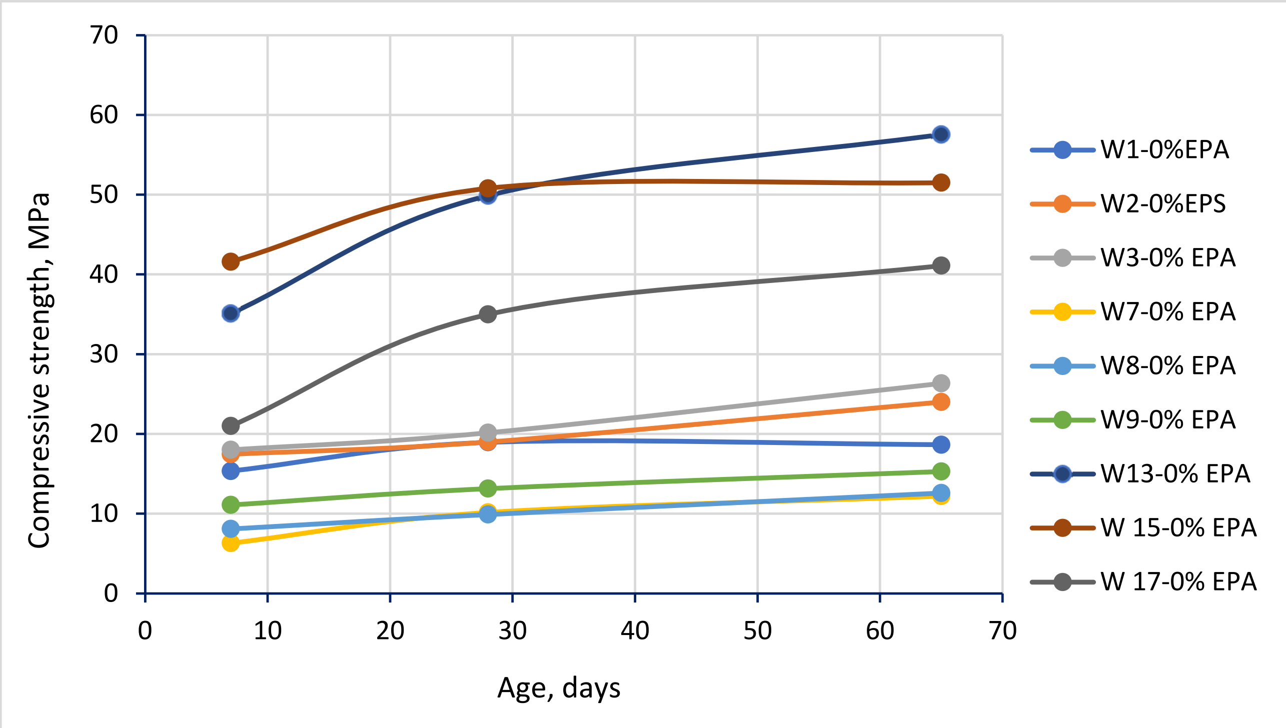

Figure 5. Compressive strength with age for mixes without perlite aggregate.

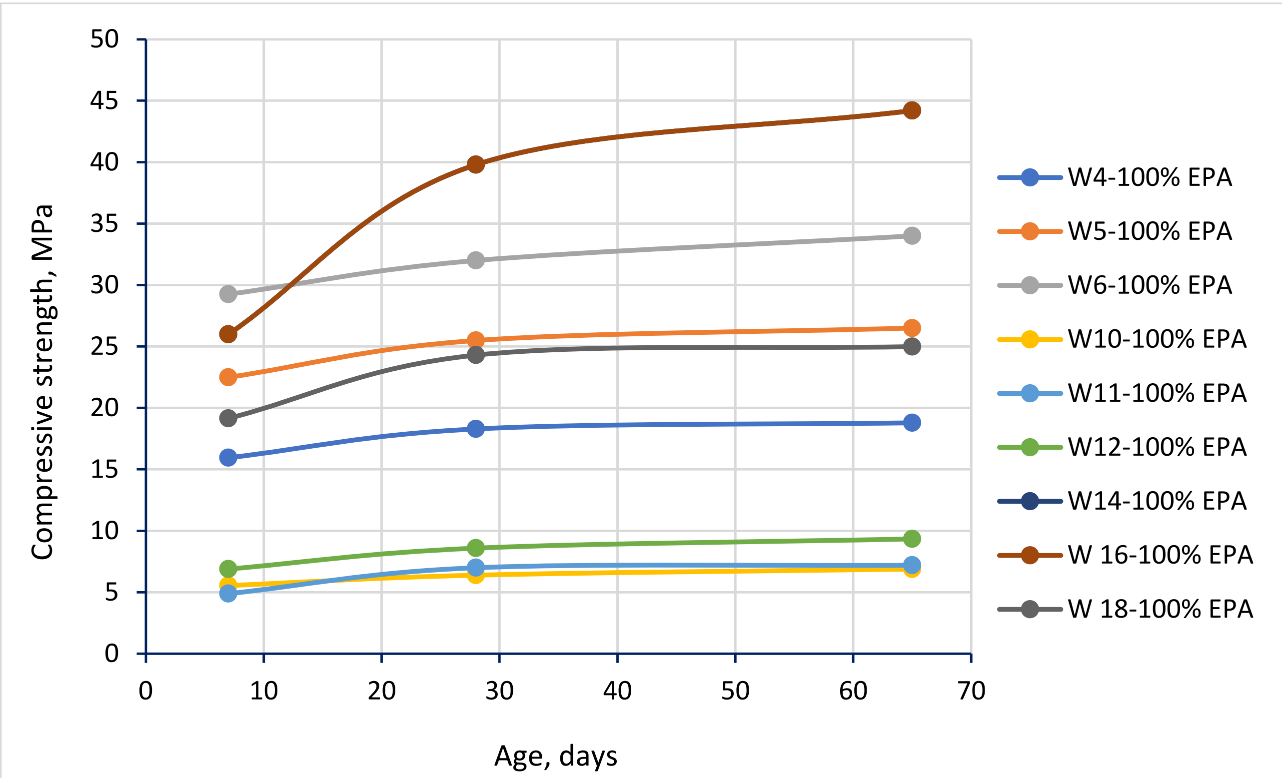

Figure 6. Compressive strength with age for mixes with perlite aggregate.

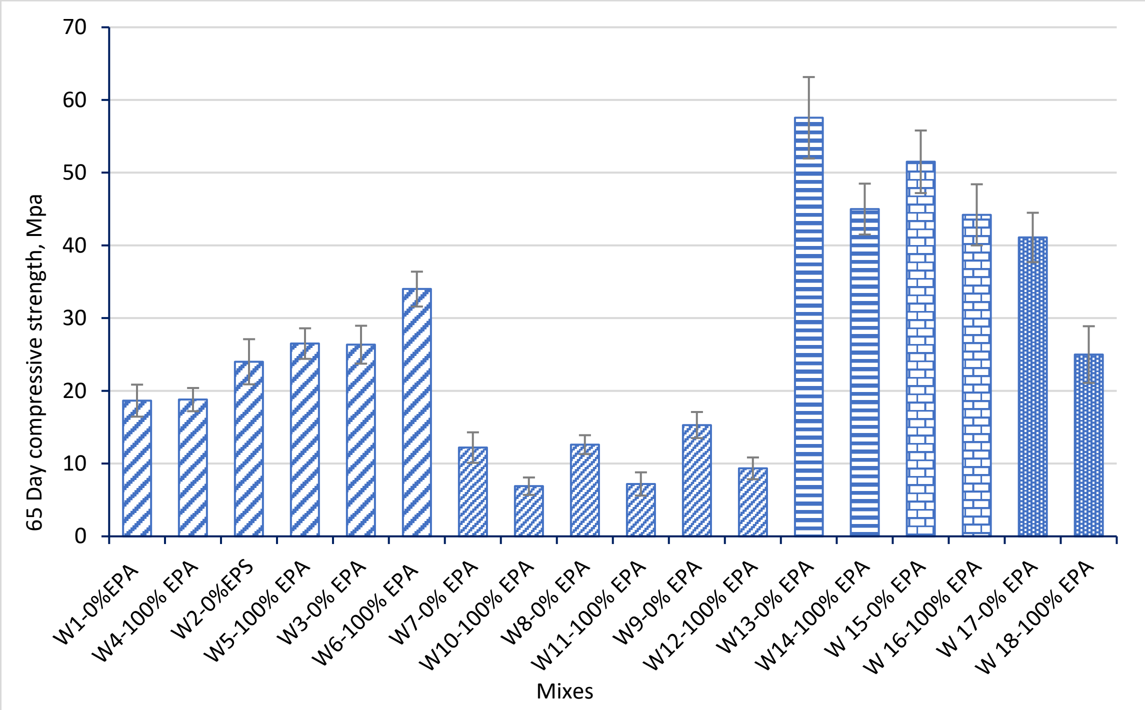

Figure 7. Compressive strength at 65 days for all mixes.

The variation in cement content across the mixes also contributed to differences in compressive strength. Mixes with higher binder content—especially those with lower W/C ratios—tended to show improved strength, in addition to the effects of aggregate packing and internal curing from EPA.

4.3. Flexural Strength

The results of the flexural strength test at a W/C ratio of 0.3 ranged from 2.9 to 4.02 MPa for mixes without perlite aggregate. When perlite was incorporated in mixes W4-100% EPA, W5-100% EPA, and W6-100% EPA, the flexural strength did not decrease, and in some cases, such as mix W6-100% EPA, it even increased slightly. This trend is consistent with compressive strength results and can be attributed to the sufficient cement content in the mixes with a W/C ratio of 0.3, where the use of lightweight aggregate did not adversely affect the structural performance characteristics, particularly since the replacement was limited to fine aggregate. Additionally, the increased coarse-to-fine aggregate ratio in mix W6-100% EPA contributed to the observed improvement in flexural strength at this W/C ratio.

At a W/C ratio of 0.4, the flexural strength values ranged from 1.51 to 1.91 MPa, which represents a decline compared to the 0.3 W/C mixes without perlite. However, when perlite aggregate was added to mixes W10-100% EPA, W11-100% EPA, and W12-100% EPA, the flexural strength did not decrease, likely because the substitution of sand with perlite aggregate did not significantly affect flexural strength due to the presence of coarse aggregate in the mixture, which provides structural support.

For the mix with a W/C ratio of 0.2, the flexural strength without perlite (W13-0% EPA) was 7.86 MPa, while the addition of perlite in mix W14-100% EPA reduced the strength to 4.54 MPa, owing to the low density and lower mechanical properties of the perlite aggregate. This effect is more evident in high-strength concrete, where the contrast in mechanical behavior between the paste and the lightweight aggregate becomes more pronounced. Using lower W/C ratios generally results in decreased structural performance, including flexural strength, due to the associated reduction in concrete density. A similar explanation applies to the mix with a W/C ratio of 0.25. Figure 8 illustrates the flexural strength results for all mixes.

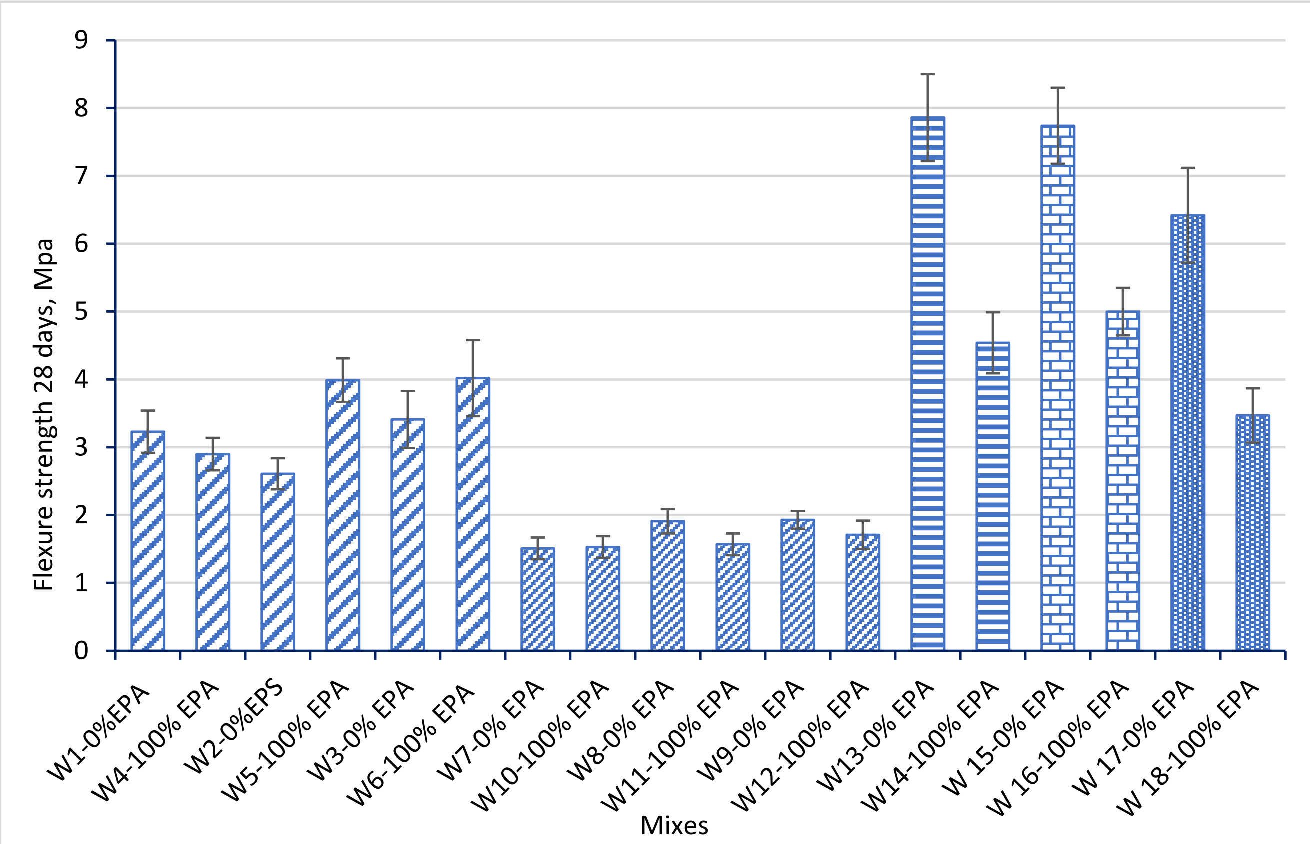

Figure 8. Flexural strength at 28 days for all mixes.

4.4. Tensile Strength

The tensile strength at a W/C ratio of 0.3 ranged from 1.65 to 2.0 MPa, and it was observed that the tensile strength of concrete did not decrease with the addition of perlite aggregate, similar to the behavior noted in compressive and flexural strength. This result can be explained by the self-curing mechanism activated at this W/C ratio, as the perlite aggregate absorbed water and gradually released it during the hydration process after hardening, thereby enhancing the mechanical properties in some mixes.

At a W/C ratio of 0.4, the tensile strength was generally lower compared to the 0.3 ratio, ranging between 0.95 and 1.0 MPa. Even when all natural sand was replaced by perlite aggregate, the tensile strength did not decrease, as the perlite contributed to better workability without compromising the internal structural resistance of the concrete.

In the mix with a W/C ratio of 0.2 (W13-0% EPA), the tensile strength reached 3.3 MPa, whereas in mix W14-100% EPA, which included perlite aggregate, it decreased to 2.6 MPa. Similarly, at a W/C ratio of 0.25 in mixes W15-0% EPA and W16-100% EPA, a slight reduction in tensile strength was noted due to the low density of the perlite aggregate. A comparable reduction was also recorded in mix W18-100% EPA, following the same trend observed in high-strength concrete containing lightweight fine aggregate. Figure 9 displays the tensile strength results over time for all mixes.

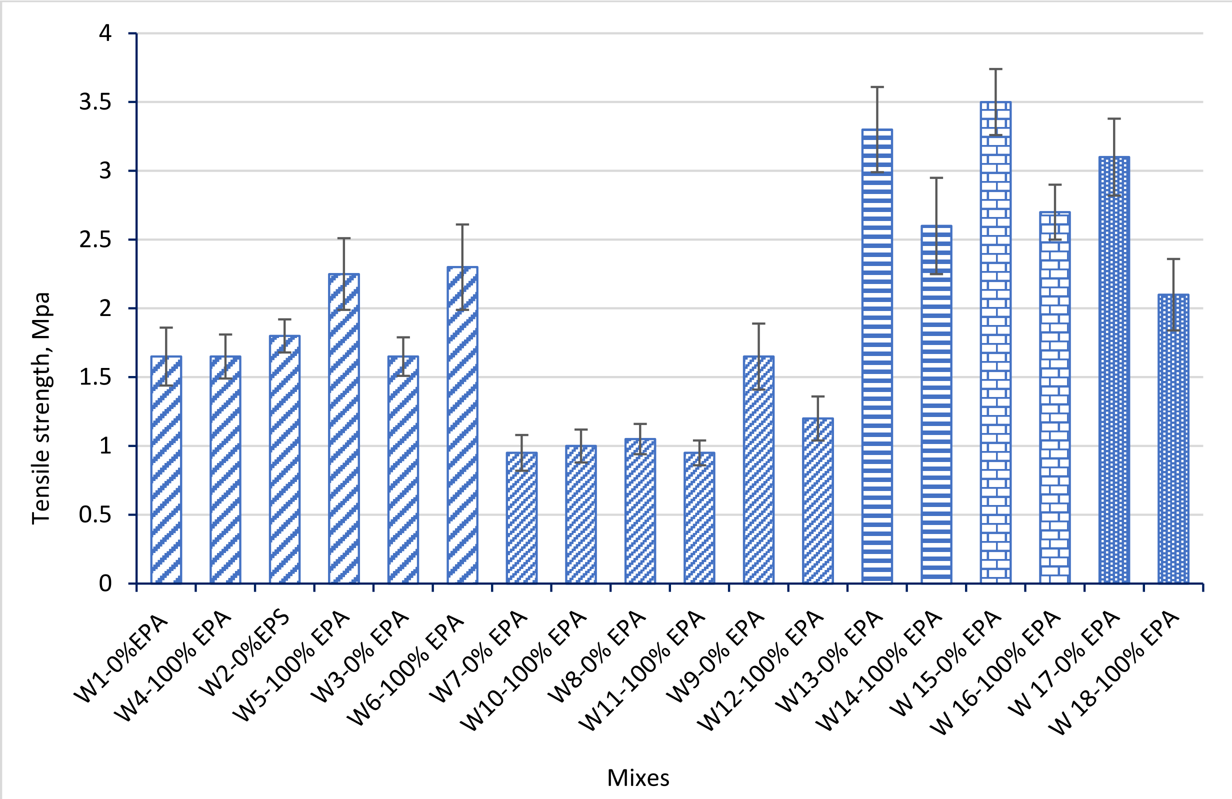

Figure 9. Tensile strength at 28 days for all mixes.

4.5. Density

At a W/C ratio of 0.3 in mixes W1-0%EPA to W6-100% EPA, the mixes without perlite aggregate were influenced by the FA/CA ratio. As the FA/CA ratio increased, the overall density of the concrete decreased, since natural sand has a lower density than natural gravel. However, when perlite aggregate was introduced, the density further decreased across all mixes, with the lowest value recorded in mix W4-100% EPA at 1772 kg/m^3, which was attributed to the very low density of the perlite aggregate.

At a W/C ratio of 0.4 in mixes W7-0% EPA to W12-100% EPA, a decrease in density was also observed as the FA/CA ratio increased, due to the lower density of natural sand. When perlite aggregate was added, the density dropped significantly across all mixes, with the lowest recorded value in mix W10-100% EPA at 1447 kg/m^3. At a W/C ratio of 0.2, the amount of sand used was minimal, as the FA/CA ratio was 0.21. Due to this low ratio, the density was high in mix W13-0% EPA (without perlite aggregate), reaching 2393 kg/m^3. In mix W14-100% EPA, where the sand was fully replaced with perlite aggregate, the density decreased to 2295 kg/m^3, although this reduction was not substantial because of the limited amount of fine aggregate. At a W/C ratio of 0.25, the FA/CA ratio was slightly higher at 0.34, resulting in a lower density in mix W16-100% EPA (with perlite) compared to mix W15-0% EPA (without perlite).

Mix W17-0% EPA, with a W/C ratio of 0.3, differed from the first six mixes in that its FA/CA ratio was lower, meaning it contained less sand. The density in mix W17-0% EPA was 2309 kg/m^3, while in mix W18-100% EPA, where perlite was used, it decreased to 2174 kg/m^3. Table 6 presents the concrete density corresponding to the FA/CA ratio for each mix, and Figure 10 illustrates the concrete density values across all mixes.

Table 6. Density of concrete with FA/CA ratio.

Mixes	Density, kg/m^3	FA/CA	Mixes	Density, kg/m^3	FA/CA
W1-0%EPA	2019	2.38	W10-100% EPA	1447	3.57
W2-0%EPS	2136	1.22	W11-100% EPA	1533	2.08
W3-0% EPA	2178	0.68	W12-100% EPA	1640	1.30
W4-100% EPA	1772	2.38	W13-0% EPA	2393	0.21
W5-100% EPA	2074	1.22	W14-100% EPA	2295	0.21
W6-100% EPA	2115	0.68	W 15-0% EPA	2338	0.34
W7-0% EPA	1932	3.57	W 16-100% EPA	2211	0.34
W8-0% EPA	1997	2.08	W 17-0% EPA	2309	0.43
W9-0% EPA	2064	1.30	W 18-100% EPA	2174	0.43

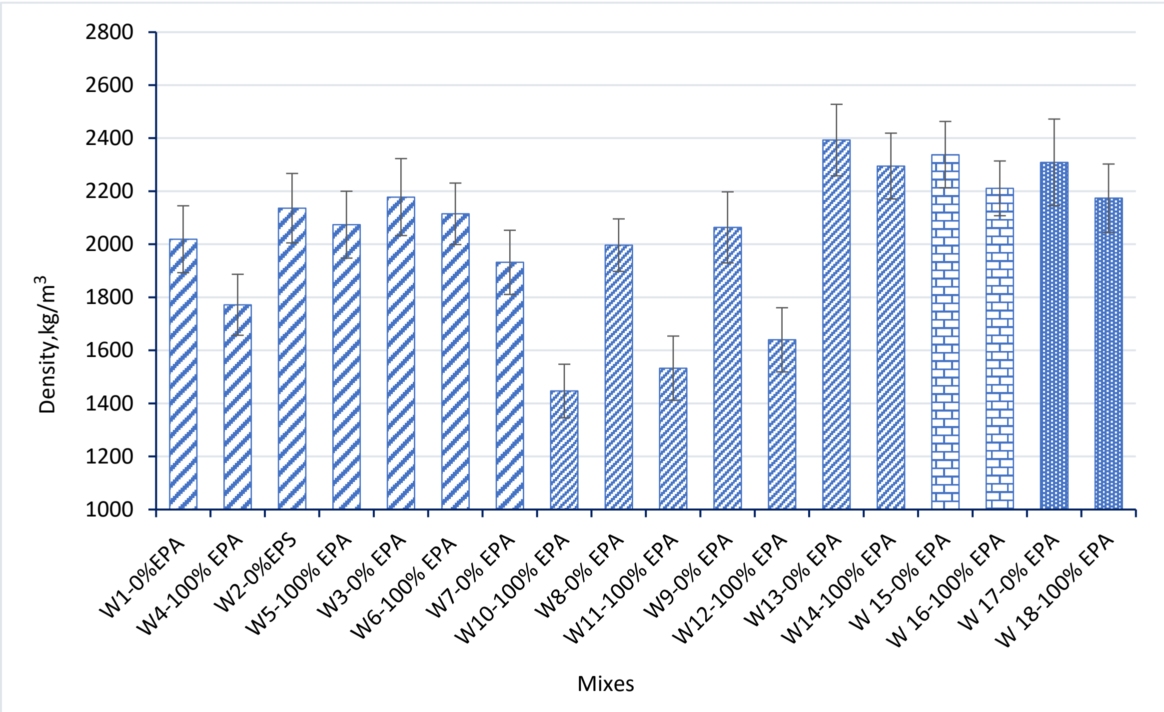

Figure 10. Oven dry density of concrete for all mixes.

4.6. Water Absorption

At a W/C ratio of 0.3 in mixes W1-0%EPA to W6-100% EPA, a decrease in water absorption was observed as the FA/CA ratio decreased in the mixes without perlite aggregate. This is because natural sand absorbs more water than gravel. When perlite aggregate was added, an increase in water absorption was noted only in mix W4-100% EPA, where it reached 6.48%, compared to 4.92% in mix W1-0%EPA. This difference is attributed to the higher quantity of sand in mix W4-100% EPA, which was entirely replaced by lightweight perlite aggregate as a result of the increased FA/CA ratio, and due to the inherently high water absorption capacity of perlite aggregate. At this W/C ratio (0.3), the perlite aggregate in mixes W5-100% EPA and W6-100% EPA functioned as a self-curing mechanism, which reduced pore formation and resulted in a corresponding decrease in water absorption.

At a W/C ratio of 0.4 in mixes W7-0% EPA to W12-100% EPA, a decrease in water absorption was again observed as the FA/CA ratio decreased in mixes without perlite aggregate. When perlite aggregate was introduced, there was a noticeable increase in water absorption—more pronounced than in the mixes with a W/C ratio of 0.3—due to the low density and high absorption capacity of the perlite aggregate, combined with the lower cement content compared to the first six mixes. For example, in mix W10-100% EPA, the absorption reached 11%. At a W/C ratio of 0.2 (mixes W13-0% EPA and W14-100% EPA), absorption values were lower than in previous mixes, primarily due to the higher cement content. Absorption in mix W13-0% EPA was 1.25%, but it increased to 1.7% in mix W14-100% EPA, a change that can also be attributed to the lower FA/CA ratio compared to earlier mixes. At a W/C ratio of 0.25 in mixes W15-0% EPA and W16-100% EPA, the results were consistent with those observed in other mixes with the same W/C ratio. Absorption was 1.4% in mix W15-0% EPA and increased to 1.7% in mix W16-100% EPA [49].

In mix W17-0% EPA, with a W/C ratio of 0.3, the water absorption was 2.85%, and when perlite aggregate was added in mix W18-100% EPA, the absorption increased to 3.77%, due to the high water absorption capacity of the perlite aggregate. Table 7 presents the dry density of the concrete mixtures along with the corresponding FA/CA ratios, and Figure 11 illustrates the dry density values for all mixes.

Table 7. Water absorption of concrete with FA/CA ratio.

Mixes	Water Absorption, %	FA/CA	Mixes	Water Absorption, %	FA/CA
W1-0%EPA	4.92	2.38	W10-100% EPA	11	3.57
W2-0%EPS	4.72	1.22	W11-100% EPA	9.45	2.08
W3-0% EPA	3.9	0.68	W12-100% EPA	6.7	1.30
W4-100% EPA	6.48	2.38	W13-0% EPA	1.25	0.21
W5-100% EPA	3.03	1.22	W14-100% EPA	1.7	0.21
W6-100% EPA	2.98	0.68	W15-0% EPA	1.45	0.34
W7-0% EPA	6.41	3.57	W16-100% EPA	2.8	0.34
W8-0% EPA	5.5	2.08	W17-0% EPA	2.85	0.43
W9-0% EPA	6.78	1.30	W18-100% EPA	3.77	0.43

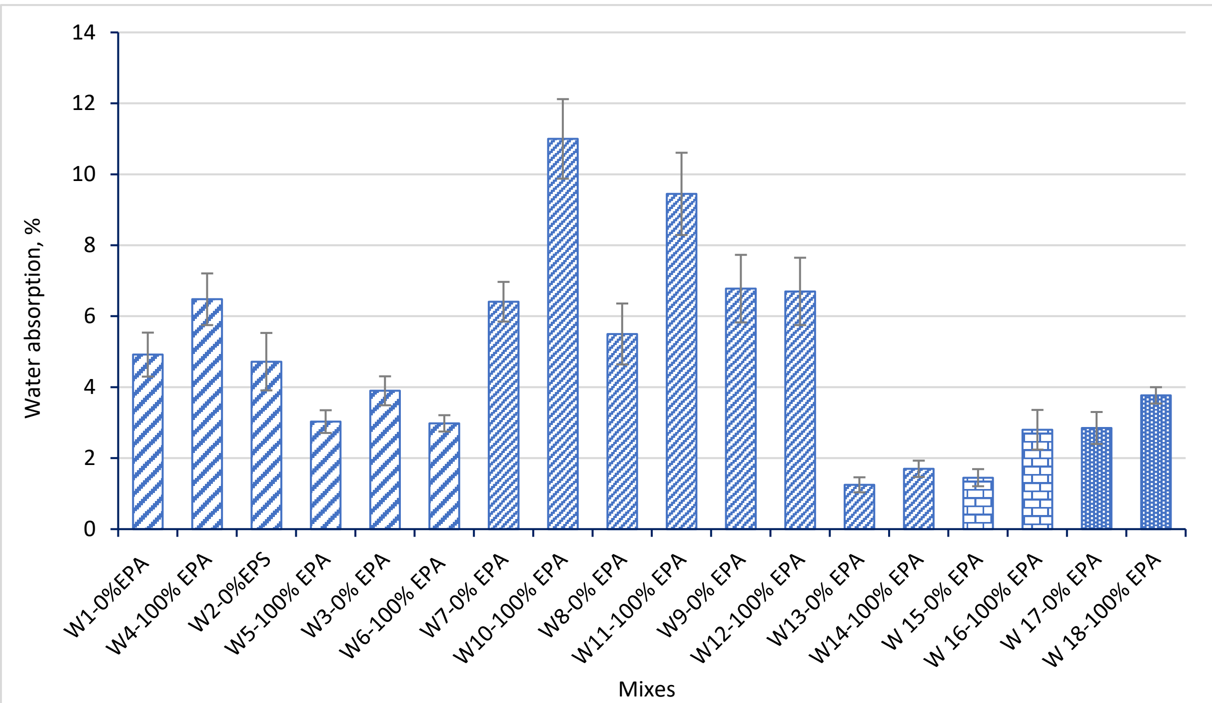

Figure 11. Water absorption of concrete for all mixes.

4.7. Thermal Conductivity

In recent years, numerous methods have been developed to conserve energy and minimize heat loss. Lightweight concrete offers a degree of thermal insulation that depends on its density and the type of aggregate used. In this study, perlite aggregate was employed as a substitute for natural sand, and thermal conductivity for all mixtures was calculated using the Valore equation [50], which relates thermal conductivity to the dry density (ρ) of lightweight concrete:

$$k = 0.00018\rho^{1.5} \tag{1}$$

where k is the thermal conductivity in W/m·K and ρ is the dry density in kg/m^3. This empirical formula has been widely used for lightweight concretes containing porous aggregates, such as expanded perlite, due to the strong relationship between material density and thermal performance. Although originally proposed in 1980, the Valore equation remains applicable and has been cited in several recent studies for estimating thermal conductivity when direct experimental measurement is not feasible. In this study, thermal conductivity measurements were not performed due to equipment limitations; hence, this model was adopted to provide a practical comparison across the different mix designs. Its assumptions are appropriate for expanded perlite concrete due to its high porosity and low thermal conductivity. There are a number of researchers who have used different equations to find the thermal conductivity of lightweight concrete [47,51].

At a W/C ratio of 0.3 in mixes W1-0%EPA to W6-100% EPA, thermal conductivity was influenced by the concrete's density, such that an increase in density resulted in higher thermal conductivity, and a decrease in density led to lower thermal conductivity. For instance, in mix W1-0%EPA, the thermal conductivity was 0.89 W/m·K, while in mix W4-100% EPA, it dropped to 0.65 W/m·K due to the incorporation of perlite aggregate. Similar trends were observed in the remaining mixes containing perlite aggregate, as the reduction in density caused by the lightweight perlite contributed to lower thermal conductivity.

At a W/C ratio of 0.4 in mixes W7-0% EPA to W12-100% EPA, the thermal conductivity ranged from 0.48 to 0.95 W/m·K, depending on the concrete density. Mix W10-100% EPA exhibited both the lowest density and the lowest thermal conductivity. For the W/C ratio of 0.2, the concrete density was higher than in the other mixes, leading to an increase in thermal conductivity. In mix W13-0% EPA, the thermal conductivity was 1.43 W/m·K, and it decreased to 1.26 W/m·K in mix W14-100% EPA due to the inclusion of perlite aggregate. At a W/C ratio of 0.25, the thermal conductivity was 1.33 W/m·K in mix W 15-0% EPA and decreased to 1.14 W/m·K in mix W 16-100% EPA as a result of the reduction in concrete density. In mix W 17-0% EPA, the thermal conductivity was 1.29 W/m·K, and it dropped to 1.09 W/m·K in mix W 18-100% EPA, which is attributed to the incorporation of perlite aggregate and the resulting decrease in density. Table 8 presents the thermal conductivity values alongside concrete density, while Figure 12 illustrates the thermal conductivity across all mixes, and Figure 13 shows the relationship between thermal conductivity and concrete density for all the mixtures.

Table 8. Thermal conductivity and density of concrete with FA/CA ratio.

Mixes	Density, kg/m^3	FA/CA	Kc, W/m·K	Mixes	Density, kg/m^3	FA/CA	Kc, W/m·K
W1-0%EPA	2019	2.38	0.89	W10-100% EPA	1447	3.57	0.43
W2-0%EPS	2136	1.22	1.039	W11-100% EPA	1533	2.08	0.48
W3-0% EPA	2178	0.68	1.09	W12-100% EPA	1640	1.30	0.55
W4-100% EPA	1772	2.38	0.65	W13-0% EPA	2393	0.21	1.43
W5-100% EPA	2074	1.22	0.96	W14-100% EPA	2295	0.21	1.26
W6-100% EPA	2115	0.68	1.01	W15-0% EPA	2338	0.34	1.33
W7-0% EPA	1932	3.57	0.8	W16-100% EPA	2211	0.34	1.14
W8-0% EPA	1997	2.08	0.87	W17-0% EPA	2309	0.43	1.29
W9-0% EPA	2064	1.30	0.95	W18-100% EPA	2174	0.43	1.09

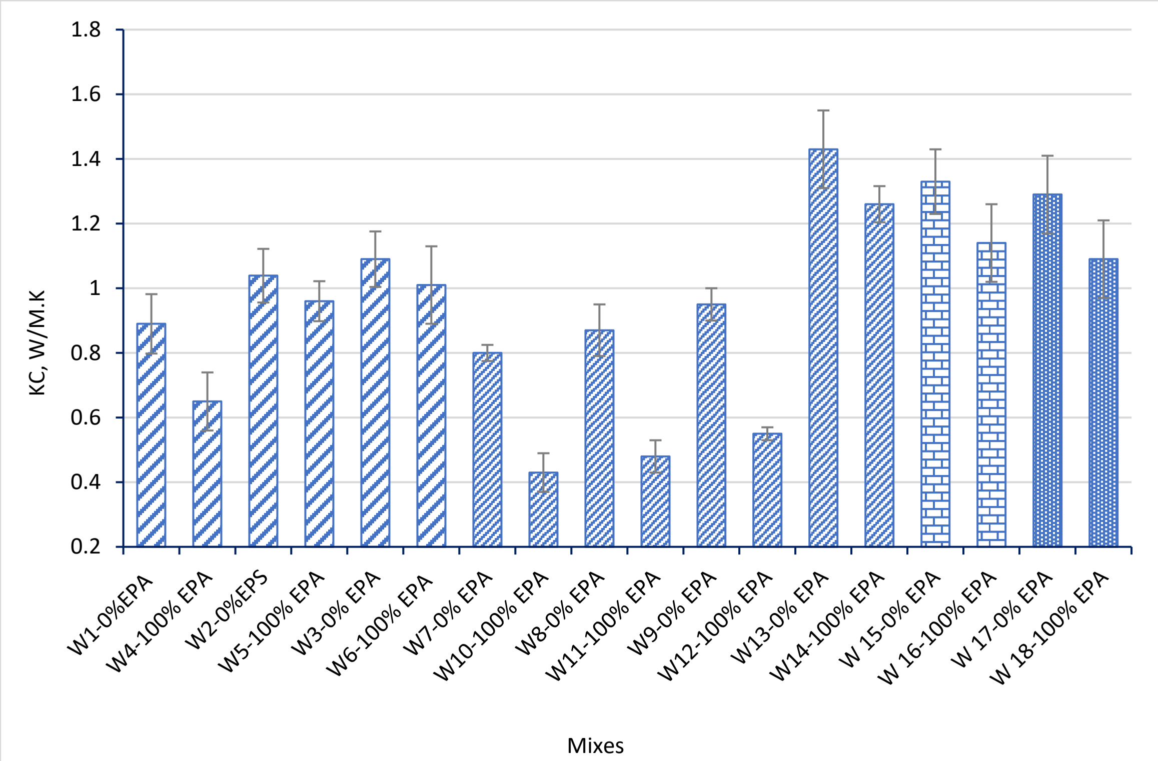

Figure 12. Thermal conductivity for all mixes.

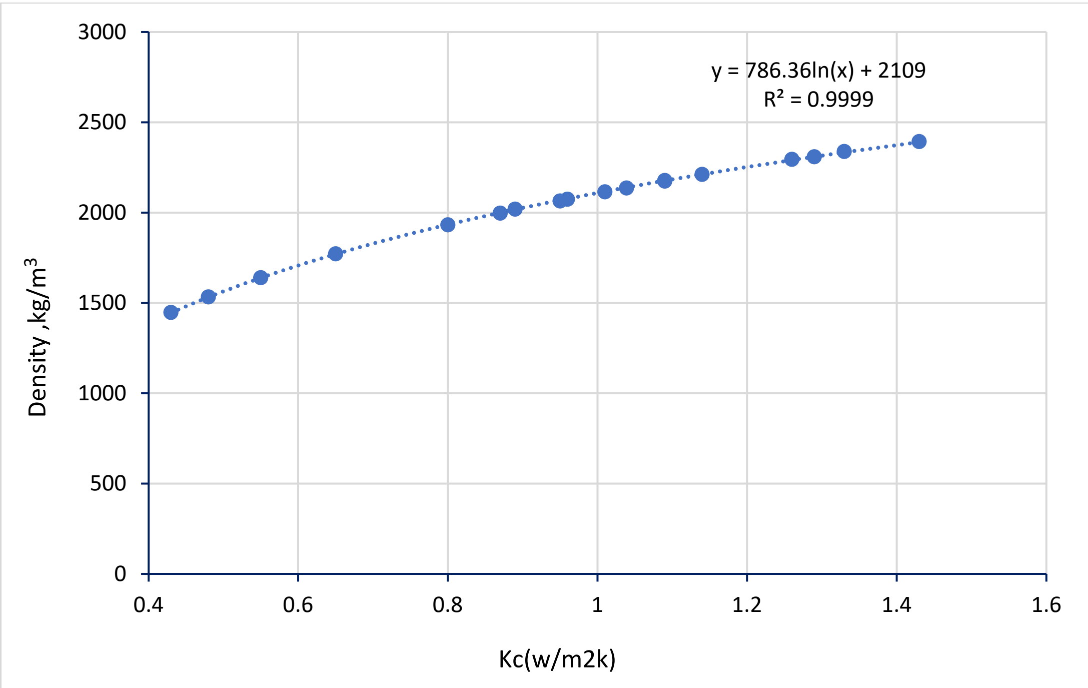

Figure 13. The relationship between thermal conductivity with density for all the mixes.

The thermal conductivity of the expanded-perlite concrete mixes in this study ranged from 0.37 to 1.27 W/m·K, depending on the W/C and FA/CA ratios. These values compare favorably with other insulating lightweight concretes. For example, foam–glass aggregates typically exhibit thermal conductivities around 0.4–0.6 W/m·K, while polystyrene bead concretes can reach as low as 0.25–0.35 W/m·K. However, EPS concretes often sacrifice mechanical strength and are less suitable for load-bearing applications. In contrast, expanded-perlite concrete offers a balanced compromise between thermal insulation and structural capacity, making it suitable for non-structural and semi-structural elements where both insulation and strength are desired. In addition, the thermal conductivity values calculated in this study are consistent with those reported in the literature for perlite-based lightweight concrete. For example, Sengul et al. [29] found thermal conductivities of 0.35 to 1.00 W/m·K for expanded-perlite mixtures. Demirboğa and Gül [52] also reported similar ranges (0.3–1.1 W/m·K), especially when silica fume and fly ash were included. Although our values derive from an empirical model (Valore equation), their alignment with reported data supports their validity.

4.8. Relationship Between Concrete Density and Compressive Strength, and Influence of the FA/CA Ratio

In this study, various FA/CA ratios were used, ranging from 0.21 to 3.57, applied to mixtures containing both perlite aggregate and natural sand. As shown in Table 9 and Figure 14, an inverse relationship was observed: as the FA/CA ratio increased, the compressive strength decreased, and vice versa, across all the mixtures. The highest FA/CA ratio of 3.57 was recorded in mix W10-100% EPA, which exhibited the lowest compressive strength at 65 days—6.9 MPa. Conversely, the highest compressive strength was observed in mix W13-0% EPA, reaching 57.55 MPa, primarily due to its low sand content and high cement content.

Table 9. FA/CA ratio with compressive strength and density.

Mixes	65 Days Compressive Strength, MPa	FA/FC	Density, kg/m^3	Mixes	65 Days Compressive Strength, MPa	FA/FC	Density, kg/m^3
W1-0%EPA	18.65	2.38	2019	W10-100% EPA	6.9	3.57	1447
W2-0%EPS	24	1.22	2136	W11-100% EPA	7.2	2.08	1533
W3-0% EPA	26.35	0.68	2178	W12-100% EPA	9.35	1.3	1640
W4-100% EPA	18.8	2.38	1772	W13-0% EPA	57.55	0.21	2393
W5-100% EPA	26.5	1.22	2074	W14-100% EPA	45	0.21	2295
W6-100% EPA	34	0.68	2115	W15-0% EPA	51.5	0.34	2338
W7-0% EPA	12.2	3.57	1932	W16-100% EPA	44.2	0.34	2211
W8-0% EPA	12.6	2.08	1997	W17-0% EPA	41.1	0.43	2309
W9-0% EPA	15.3	1.3	2064	W18-100% EPA	25	0.43	2174

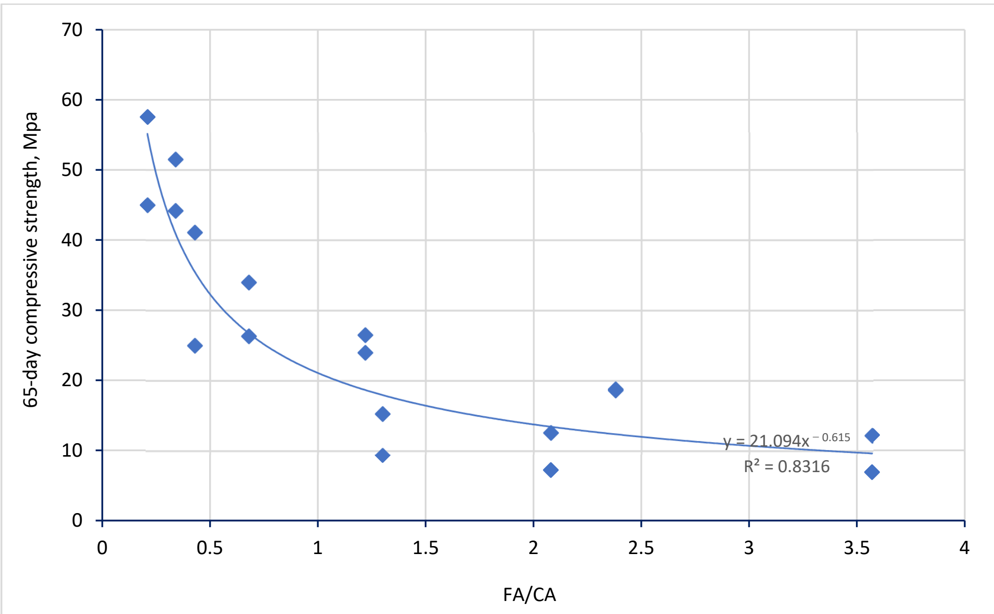

Figure 14. The relationship between density and 65 days of compressive strength.

Regarding concrete density, two key relationships were identified: first, compressive strength generally increased with higher concrete density; second, the use of lightweight aggregates, such as perlite, significantly reduced the density, as illustrated in Figure 15.

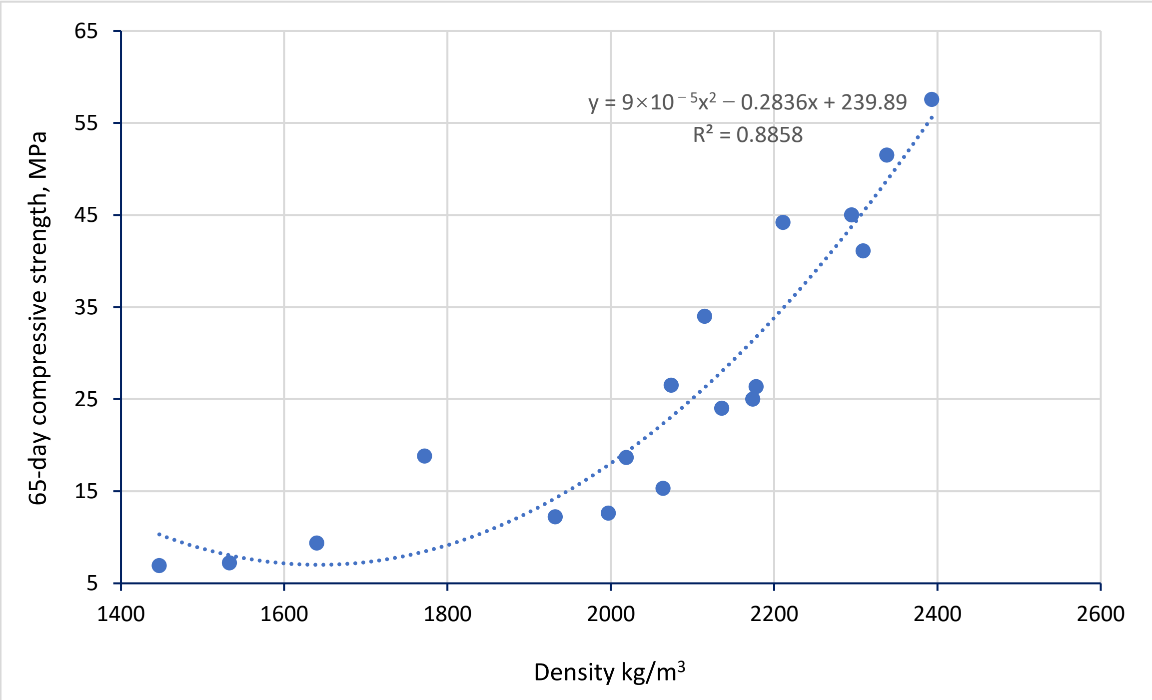

Figure 15. Relationship between density and compressive strength.

5. Conclusions

In this study, 18 concrete mixtures were examined using different water-to-cement (W/C) and fine-to-coarse aggregate (FA/CA) ratios, with the natural sand completely replaced by lightweight perlite aggregate. The structural performance characteristics, thermal conductivity, and density of all the mixtures were analyzed, resulting in the following conclusions:

- The results of the concrete slump test indicated that the use of perlite aggregate led to a significant increase in slump. This is attributed to the fact that the perlite aggregate was used in a saturated surface-dry (SSD) condition, having been pre-soaked and sprayed with water 24 h prior to mixing. Due to its high absorption capacity, the perlite retained moisture, thereby increasing the workability of the concrete. Additionally, the magnitude of this increase was influenced by the W/C ratio—higher W/C ratios resulted in greater slump values. For example, in mix W10-100% EPA, the slump increased by 120% compared to a mix of W7-0% EPA.
- The compressive strength at 65 days for mixes W1-0%EPA to W6-100% EPA did not decrease despite the complete replacement of sand with perlite aggregate; in fact, mix W6-100% EPA exhibited a 29% increase in compressive strength. However, in mixes W7-0% EPA to W12-100% EPA, the compressive strength declined, with an average reduction of 41%. At a W/C ratio of 0.2, the compressive strength in mix W14-100% EPA decreased by 21% compared to mix W13-0% EPA. At a W/C ratio of 0.25, mix W 16-100% EPA showed a 14% reduction in strength when compared to mix W15-0% EPA. Similarly, mix W18-100% EPA experienced a 39% decrease in compressive strength relative to mix W17-0% EPA.
- The addition of perlite aggregate to the first six mixes did not result in any loss of flexural performance. In fact, mix W6-100% EPA demonstrated a 17% increase in

flexural strength compared to mix W3-0% EPA. In mixes W7-0% EPA to W12-100% EPA, the slight reduction in flexural strength observed with perlite aggregate was minimal and can be regarded as insignificant. However, in high-strength mixes, more substantial reductions were recorded: mix W14-100% EPA exhibited a 42% decrease in flexural strength compared to mix W13-0% EPA, mix W16-100% EPA showed a 35% decrease compared to mix W15-0% EPA, and mix W18-100% EPA experienced a 45% decrease compared to mix W17-0% EPA.

- When analyzing the tensile test results for concrete at a W/C ratio of 0.3 in mixes W1-0%EPA to W6-100% EPA, the tensile strength did not decrease. In fact, mix W6-100% EPA showed a 39% increase compared to mix W3-0% EPA. For mixes W7-0% EPA to W12-100% EPA, with a W/C ratio of 0.4, tensile strength generally remained stable, except for mix W12-100% EPA, which exhibited a 27% decrease compared to mix W9-0% EPA. At a W/C ratio of 0.2, mix W14-100% EPA showed a 21% reduction in tensile strength compared to mix W13-0% EPA. Similarly, at a W/C ratio of 0.25, mix W16-100% EPA experienced a 22% decrease in tensile strength compared to mix W15-0% EPA, and mix W18-100% EPA showed a 32% decrease relative to mix W17-0% EPA.
- The results of the density test revealed a decrease in density for all mixes containing perlite aggregate; however, this reduction was influenced by the W/C ratio and the FA/CA ratio. The average density decrease for the first group of mixes was 5.93%, with the maximum reduction occurring in mix W4-100% EPA at 12%. For mixes W7-0% EPA to W12-100% EPA, the average density decrease was 22.6%, with a peak reduction of 25% in mix W10-100% EPA. At a W/C ratio of 0.2, mix W14-100% EPA showed a 4% decrease in density compared to mix W13-0% EPA. In mixes W 15-0% EPA and W16-100% EPA with a W/C ratio of 0.25, the density in mix W16-100% EPA decreased by 5.4%, while in mix W18-100% EPA, the density reduction was 5.8% compared to mix W17-0% EPA.
- The absorption test results for the first six mixes were significantly influenced by the FA/CA ratio. Mix W4-100% EPA exhibited a 31% increase in absorption compared to mix W1-0%EPA, while mix W5-100% EPA showed a 35% decrease relative to mix W2-0%EPS, and mix W6-100% EPA showed a 23% decrease compared to mix W3-0% EPA. For mixes W7-0% EPA to W12-100% EPA, which had lower cement content than the first six mixes, absorption increased notably; mix W10-100% EPA showed a 71% increase compared to mix W7-0% EPA, and mix W11-100% EPA also exhibited a 71% increase compared to mix W8-0% EPA. In high-strength mixes, absorption in mix W14-100% EPA increased by 36% compared to mix W13-0% EPA, mix W16-100% EPA showed a 93% increase over mix W15-0% EPA, and mix W18-100% EPA showed a 32% increase compared to mix W17-0% EPA.
- The thermal conductivity of mixes incorporating perlite aggregate decreased significantly due to the material's lightweight nature. In mixes W4-100% EPA, W5-100% EPA, and W6-100% EPA, thermal conductivity decreased by 26.9%, 7.6%, and 7.3%, respectively, compared to mixes W1-0%EPA, W2-0%EPS, and W3-0% EPA. In mixes W10-100% EPA, W11-100% EPA, and W12-100% EPA, the reductions were 46.2%, 44.8%, and 42% when compared to mixes W7-0% EPA, W8-0% EPA, and W9-0% EPA. In high-strength mixes, thermal conductivity decreased by 11% in W14-100% EPA, 14.2% in W16-100% EPA, and 15% in W 18-100% EPA relative to mixes W13-0% EPA, W15-0% EPA, and W17-0% EPA, respectively.
- The optimal mix for high-strength concrete was found to be mix W16-100% EPA, in which natural sand was entirely replaced with perlite aggregate. This mix achieved a compressive strength of 44.65 MPa, a thermal conductivity of 1.14 $W/m^2{\cdot}K$, and a density of 2211 kg/m^3, offering enhanced thermal insulation and reduced weight. For

lightweight concrete applications not exposed to structural loads, the preferred mix is W4-100% EPA, with a compressive strength of 18.8 MPa, a density of 1772 kg/m^3, and a thermal conductivity of 0.65 W/m·K. Although the thermal conductivity results aligned well with published data for perlite concretes, future studies should incorporate direct experimental measurements to validate and refine the estimated thermal performance.

- While the results suggest that the porous structure of expanded perlite aggregate contributes to internal curing and improved strength retention, no direct microstructural evidence (e.g., SEM) was provided to confirm the mechanism. Future studies should incorporate microstructural analysis of the interfacial transition zone and pore structure to better understand the self-curing behavior and its role in hydration dynamics.

While this study provides a comprehensive analysis of concrete behavior incorporating expanded perlite, it is important to note certain additional limitations. All mixes used a single particle size range of perlite aggregate; however, particle size and grading may significantly affect packing density, strength, and thermal performance. In addition, since aggregate grading significantly affects the porosity, packing density, and strength of concrete, future research should also explore the influence of perlite particle size on both mechanical and durability properties. In addition, long-term durability testing such as freeze–thaw resistance, wet–dry cycles, permeability, or carbonation, which are essential for evaluating the long-term performance of concrete in different environmental conditions, were not included in this study. Future research should investigate these aspects to confirm the practical suitability of expanded perlite-based concrete in structural and non-structural applications.

While this study presents a comprehensive experimental evaluation of 18 concrete mixes, no statistical modeling (e.g., ANOVA or multivariate regression) was conducted to isolate the influence of individual variables. Future research could incorporate such methods to quantitatively assess the significance and interaction effects of mix parameters such as the W/C ratio, FA/CA ratio, and perlite content. This would support more data-driven optimization of lightweight concrete performance. Also, while this study provides a performance comparison across 18 concrete mixes, no formal optimization method was applied. Future work could benefit from the use of multi-objective optimization techniques—such as desirability analysis, statistical modeling, or machine learning—to systematically identify mix designs that best satisfy combined targets for mechanical strength, low density, and thermal insulation.

In spite of the above, the findings of this study highlight the practical potential of expanded perlite concrete for real-world applications. The reduced thermal conductivity and weight make it highly suitable for use in building envelopes, partition walls, and precast non-structural elements where thermal insulation is desired. Additionally, optimized mixes like W16-100% EPA demonstrate that it is feasible to design structurally competent lightweight concrete with enhanced energy efficiency, supporting sustainable construction practices. In addition, the findings of this laboratory-scale investigation provide a basis for further research at a semi-industrial scale. Future studies are planned to evaluate the behavior of optimized EPA-based mixes in structural elements such as slabs or precast panels, with the goal of assessing mechanical performance, thermal efficiency, and constructability under realistic conditions.

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