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Strength Performance of Different Lightweight Concrete

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ABSTRACT

This study investigates the strength performance of different lightweight concrete using polystyrene, palm kernel shell, and pumice as replacements for conventional coarse aggregates in a grade 15 concrete using 1:2:4 mix ratio. Lightweight concrete offers potential advantages in reducing structural weight while maintaining adequate strength for various applications. A control mix of concrete with 1:2:4 mix ratio was prepared to serve as the control sample. Compressive, split tensile, and flexural strength tests were used to assess the mechanical characteristics of lightweight and control concrete after 7, 14, 21, and 28 days of curing. Additionally, slump tests were used to gauge workability, and water absorption tests were used to gauge porosity. The results showed that, in contrast to the normal concrete density of at least 2400 kg/m³, the lightweight aggregates significantly reduced the density of the concrete to values within the lightweight concrete range (1402–1979 kg/m³). With a compressive strength of 11.22 MPa at 28 days (about 70% of the control) and better flexural and tensile strength than other lightweight mixes, pumice was the most effective lightweight aggregate overall. Although polystyrene demonstrated the lowest structural performance (2.05 MPa at 28 days), it gave exceptional moisture resistance and intermediate strength (6.30 MPa at 28 days) compared to palm kernel shell. The high porosity of pumice (15%), the low absorption of polystyrene (0.3%), and the intermediate value of palm kernel shell (8%), was all highlighted by water absorption tests. According to the results, polystyrene is a good lightweight aggregate for non-structural or insulating applications, palm kernel shell is recommended for moderate-strength, sustainable applications, and pumice is recommended for applications where strength and weight reduction must be balanced. Granite is still the best material for strong structural components.

Keywords: Lightweight concrete, Compressive strength, Pumice aggregate, Palm kernel shell, Polystyrene beads, Structural performance, Water absorption, Concrete density

Introduction

Concrete is a robust and long-lasting material, yet one of its physical properties can be challenging to deal with. Its typical densities are around 2400 kg/m3 and are regarded normal (Poloju *et al*., 2025; Kumar *et al*.,2021). This difficulty is compounded when modern concrete technologies like precast concrete, prefabricated concrete, and offsite construction are employed. It increases structural deadloads, needing a significant capacity for lifting cranes and vehicles for transfer. The need for larger cranes and trucks results in cost restrictions and increased environmental impact (Prasittisopin *et al.,* 2022; Casanovas-Rubio *et al.,* 2017). This issue can be resolved by using lightweight concrete. As a result, lightweight concrete was introduced and widely used in building applications where structural weight reductions areIts typical densities are around 2400 kg/m3 and are regarded normal (Poloju *et al.,* 2025; Kumar *et al.,*2021). This difficulty is compounded when modern concrete technologies like precast concrete, prefabricated concrete, and offsite construction are

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employed.

Lightweight concrete is utilized mainly for the reduction in the overall weight of structures which lowers the loads on foundations and improves energy efficiency through better insulation. This weight reduction also makes the material easier to handle and transported, speeding up construction and lowering labor and transport costs. Lightweight concrete incorporates lightweight aggregates like expanded clay, shale, palm kernel shell, perlite, and pumice, which reduces its density in comparison with the normal or conventional concrete (Graybeal, 2013; Jassim *et al.,* 2024). Lightweight concrete typically has a density of 1440–1840 kg/m³, while conventional concrete has a density of about 2400 kg/m³ (Kumar *et al.,* 2021). Though it is still comparatively understudied in comparison to traditional concrete, research on the strength of lightweight concrete has been receiving more attention in recent years. The compressive strength and durability characteristics of structural lightweight concrete with fine expanded glass and clay aggregates were investigated by Rumsys *et al.* (2018). Their results offer insightful information about how various lightweight concrete mixtures behave, showing that the selection of aggregate is a critical factor in determining durability and mechanical qualities.

The use of substitute materials for cement in lightweight concrete blocks, such as wood fiber waste, rice husk ash, and limestone powder waste, was investigated by Torkaman *et al.* (2014). Additionally, Elsherbiny (2023) investigated the possibility of using steel and polypropylene fibers to improve the structural behavior of sustainable reinforced lightweight concrete beams made from crushed clay bricks. The study demonstrated the feasibility of using waste materials in lightweight concrete production, offering a chance to improve mechanical properties while lowering environmental impact. The study of Chung *et al.* (2017) evaluated the effects of different gradings of lightweight aggregates on concrete properties, indicating that careful selection of aggregates is critical for optimizing performance. Upasiri *et al.* (2021) revealed that lightweight concrete made with pumice aggregate exhibits superior fire performance compared to normal lightweight aggregate concretes, thus making it a suitable choice for fire-resistant construction materials.

Additionally, Šeputytė-Jucikė *et al.* (2023) examined the performance features of lightweight concrete composed of crushed expanded polystyrene and expanded glass, offering insights into how various aggregates affect lightweight concrete's characteristics. Their results highlight how crucial aggregate choice is to the mechanical and long-term performance of lightweight concrete. Furthermore, Spiesz *et al.* (2013) investigated the creation of lightweight composites based on cement, emphasizing durability-related characteristics like electrical resistivity, freeze-thaw resistance, water-permeable porosity, capillary water absorption, chloride transport properties, and alkali-silica reaction. This comprehensive investigation presents a holistic view of the durability aspects associated with lightweight concrete, emphasizing its relevance in modern construction practices.

Materials and Methods

Materials

Dangote Limestone Cement, a grade 42.5N that satisfies the physical specifications listed in BS EN 197-1:2011, was used in this investigation. A quarry near Akure provided fine and coarse aggregates. In this study, the coarse aggregate in the concrete mix was completely replaced with three lightweight materials: pumice, palm kernel shell, and polystyrene. After being purchased from a nearby market, the pumice was crushed into sizes that met the specifications for coarse aggregate. The Polystyrene was Obtained from an electronic store and broken down to the required sizes for mixing while the Palm Kernel Shell was also Collected from palm kernel crushers and thoroughly dried

These aggregates were sourced and processed in accordance with BS EN 12620. Potable water that is free from impurities, was employed in the mixing process. Figure 1 (a-c) shows the material utilized for the study.

Mix Design

A typical 1:2:4 ratio (cement: fine aggregate: coarse aggregate) was used to mix the components of grade 15 concrete, with lightweight aggregates (pumice, palm kernel shell, and polystyrene) substituting the coarse aggregate in different mixes. For comparison, this mix design guarantees uniformity among various samples. Granite, a common natural aggregate, was used to create a control mix that was used to compare the lightweight concrete samples' performance. The ratio of water to cement was 0.5. Batching was done by weight after the ingredients were hand combined.

Casting of Specimens

To keep the concrete from sticking, the cube moulds (150 mm x 150 mm x 150 mm), cylinder moulds (150 mm diameter x 300 mm height), and beam moulds (100 mm x 100 mm x 500 mm) were first cleaned and oiled. The molds were filled with three layers of concrete. A tamping rod was used to manually compact each layer to remove air pockets and guarantee homogeneity. After all the layers were in place, a trowel was used to level and smooth the concrete's top surface, creating a flat finish. Pictures of recently created samples are displayed in Figure 2.

Figure 1a. Pumice

Figure 1b. Polystyrene

Figure 1c. Palm kernel shell

Figure 2. Placement of samples into cube, beam and cylinder mold

Bulk Density

It is crucial to evaluate the bulk density of the samples to confirm that the concrete mixes meet the requirements for lightweight concrete. Lightweight concrete is often defined as having a density of less than 2,000 kg/m³ (Zareef, 2010; Thienel *et al.,* 2020). This criterion aids in verifying that the materials can attain the desired lightweight qualities without sacrificing functionality. The concrete's density was estimated via the use of Equation 1.

$$\text{Density}(\rho) = \frac{W}{V} \quad (1)$$

Where:
ρ is Concrete's density (kg/m³)
W is Total weight (kg)

V is Volume of the concrete (m^3)

Compressive Strength Test

Compressive strength testing was carried out in accordance with BS EN 12390-3 (2009). Following seven, fourteen, twenty-one, and twenty-eight days of curing in a curing tank, the concrete cubes were removed and subjected to a compressive strength test. Specimens were loaded until they failed using a compression testing device that met the BS EN 12390-4 (2019) standard. Equation (2) was used to determine the strength once the specimens' maximum loads were recorded.

$$\text{Compressive strength of concrete } (Fc) = \frac{P}{A} \qquad (2)$$

Where A is the cross-sectional area (in square millimetres) and P is the maximum load (in Newtons).

Tensile Strength Test

The test was conducted in accordance with BS EN 12390-6, (2009). Equation 3 was employed in the calculation of split tensile strength values.

Tensile strength of concrete

$$(Ft) = \frac{2P}{\pi LD} \qquad (3)$$

Flexural Strength Test

The flexural strength test was performed in line with BS EN 12390-5 (2009) to determine the resistance of the various concrete beam specimens to bending. The flexural strengths were calculated, and the maximum loads supported by each specimen were determined.

Equation 4 was used to determine flexural strength.

$$\text{Flexural Strength of concrete } (Ff) = \frac{PL}{bd^2} \qquad (4)$$

P is the maximum load (in Newtons), L is the span length (in millimeters), b is the breadth (in millimeters), and d is the depth (in millimeters).

Water Absorption Test

The concrete specimens were weighed and stored in a curing tank for 28 days to calculate the water absorption rate in compliance with BS 1881-122, (2011). The samples were swiftly dried with a cloth until there was no more water on the surface after being shaken to remove any excess surface water. After the specimens were reweighed, the percentage of water absorption for each specimen was calculated using Equation (5).

$$\text{Water Absorption} = \frac{Ws - Wd}{Wd} \times 100\% \qquad (5)$$

where Ws is the weight of the saturated sample and Wd is the weight of the dry sample.

Results and Discussion

Bulk Density

The density results for the control mix and the lightweight aggregate mixes (pumice, polystyrene, and palm kernel shell) are presented in figure 3.
Figure 3, on the other hand, illustrates how the lightweight aggregates—pumice, polystyrene, and palm kernel shell—showed noticeably lower densities, indicating their low-mass or porous properties. Despite being significantly lighter, pumice strikes a balance between weight reduction and sufficient strength, making it appropriate for structural applications like slabs and beams where a

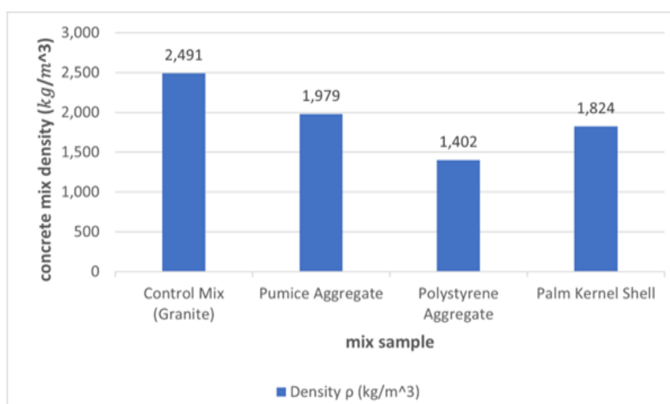

Figure 3. Density Comparison of Control and Lightweight Aggregate Concrete

lower dead load is desired. Its high porosity, however, raises questions about long-term durability and water absorption. Although polystyrene produced the lowest density, highlighting its potential for non-structural uses and thermal insulation, its weak binding with cement pastes compromises strength and limits its use in structural applications. Palm kernel shell demonstrated an intermediate density, providing a sustainable substitute with a modest potential for strength; however, due to its irregular particle shape and absorptive nature, mix modifications are required to improve performance.

Structural lightweight concrete is defined by the EN-1992 standard as having an oven-dry density of at least 800 kg/m^3 and a maximum of 2000 kg/m3. According to the Poloju *et al.* (2025) study, concrete must have a density between 1400 and 1960 kg/m^3 to be classified as lightweight concrete. By comparing the data, it is possible to determine that all the materials—aside from the control sample—are designated as lightweight concrete with recorded densities ranging from 1402 to 1979 kg/m^3, whereas the control is classified as conventional concrete. Normal weight concrete is suitable for creating reinforced concrete members since it has a density of between 2200 and 2600 kg/m^3 (Konitufe *et al.,* 2023).

Compressive Strength Analysis

Figure 4 displays the findings of the compressive strength test conducted over 7, 14, 21, and 28 days for several lightweight aggregates (pumice, polystyrene, and palm kernel shell) and the control mix.

According to figure 4, the control mix continuously showed the maximum compressive strength during all curing times. Values increased from 10.37 MPa at 7 days to 16.01 MPa at 28 days, which is in line with the grade 15 concrete specification in BS EN 206:2013. Given that granite is a robust and thick aggregate that provides superior load resistance and bonding with the cement matrix, this superior performance is anticipated. The 54.3% strength increase throughout the curing process is consistent with how normal concrete typically behaves.

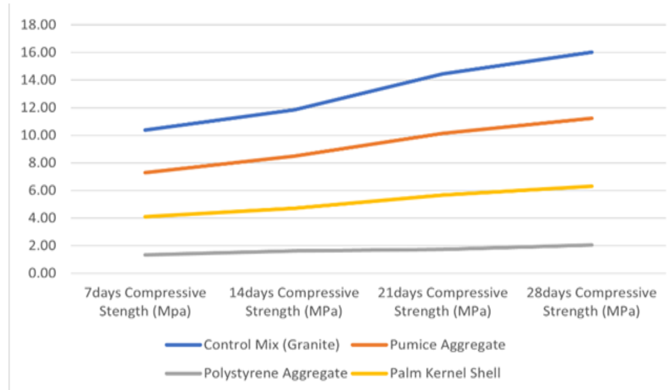

Figure 4: Compressive Strength of Concrete Mixes.

In accordance with the study of Tuncer *et al.* (2025), which found lower compressive strength when coated pumice was used as aggregate in concrete, pumice aggregate showed moderate compressive strength, recording 7.30 MPa at 7 days and 11.22 MPa at 28 days. This represents roughly 70% of the control mix strength at 28 days. This conclusion is supported by the study of Shafiq *et al.* (2021), which found that the compressive strength of pumice lightweight aggregate concrete was much lower (49%) than that of conventional concrete. Pumice performs well among lightweight aggregates even though its porous structure lowers its density and compressive strength when compared to granite. The continuous hydration process characteristic of lightweight concrete is shown in the 53.7% strength improvement over time.

The lowest compressive strength values were found in polystyrene aggregate, which increased from 1.33 MPa at 7 days to 2.05 MPa at 28 days—just 12.8% of the strength of the control mix at that point. When polystyrene was added to lightweight concrete, the study by Shah *et al*. (2024) found that the compressive strength decreased by 32, 50, and 71% when compared to the control sample. In the study by El Gamal *et al.* (2024), the compressive strength dropped between 87% and 94% for the compacted samples and between 97% and 98% for the uncompacted samples.

This poor performance is due to polystyrene's non-structural properties, including its lack of rigidity and weak bonding with cement. The slight increase in strength over time indicates limited hydration or consolidation due to the material's inherent characteristics.

With compressive strength values increasing from 4.10 MPa at 7 days to 6.30 MPa at 28 days, palm kernel shell aggregate outperformed polystyrene but performed noticeably worse than the control mix, reaching 39.4% of the control strength at 28 days. According to study of Sobuz *et al.* (2023), the use of palm kernel shell in lightweight concrete reduced the compressive strength by 44.73%, 50.83%, 53.33%, and 57.22% in 28 days compared to 10%, 15%, 20%, and 50%. Furthermore, Kumar *et al*. (2022) found that the compressive strength of lightweight aggregate concrete (LWAC) declined rapidly as the proportion of traditional aggregates substituted with palm kernel shell rose. Its modest performance can be attributed to a better connection with the cement matrix than polystyrene. However, its small weight and probable brittleness limit its overall compressive strength.

Tensile Strength Analysis

The result of tensile strength is presented in figure 5. Figure 5 shows that the tensile strength values for the control mix increased steadily and consistently across the curing period. Starting at 1.90 MPa on the seventh day, the value rises to 2.69 MPa after 28 days, indicating appropriate hydration and binding growth between cement paste and aggregates. These results are consistent with ordinary concrete, demonstrating the dependability and strength of granite as a coarse aggregate in tension-bearing applications. The pumice aggregate shows promising tensile strength improvement. Tensile strength improves from 1.63 MPa on the seventh day to 2.28 MPa on the 28th day. While somewhat lower than the control mix, pumice has good tensile capabilities compared to other lightweight aggregates, making it ideal for applications that require moderate tensile strength.

Tensile strength values for polystyrene are much lower, beginning at 0.26 MPa on day seven and rising slightly to 0.38 MPa on day twenty-eight. Polystyrene's intrinsic fragility and poor binding with cement paste are reflected in this low strength improvement, suggesting that its use is best suited for non-structural or insulating applications where tensile strength is not crucial. When compared to polystyrene, palm kernel shell obtains moderate tensile strength values, however it still falls well short of pumice and the control mix. Its promise for

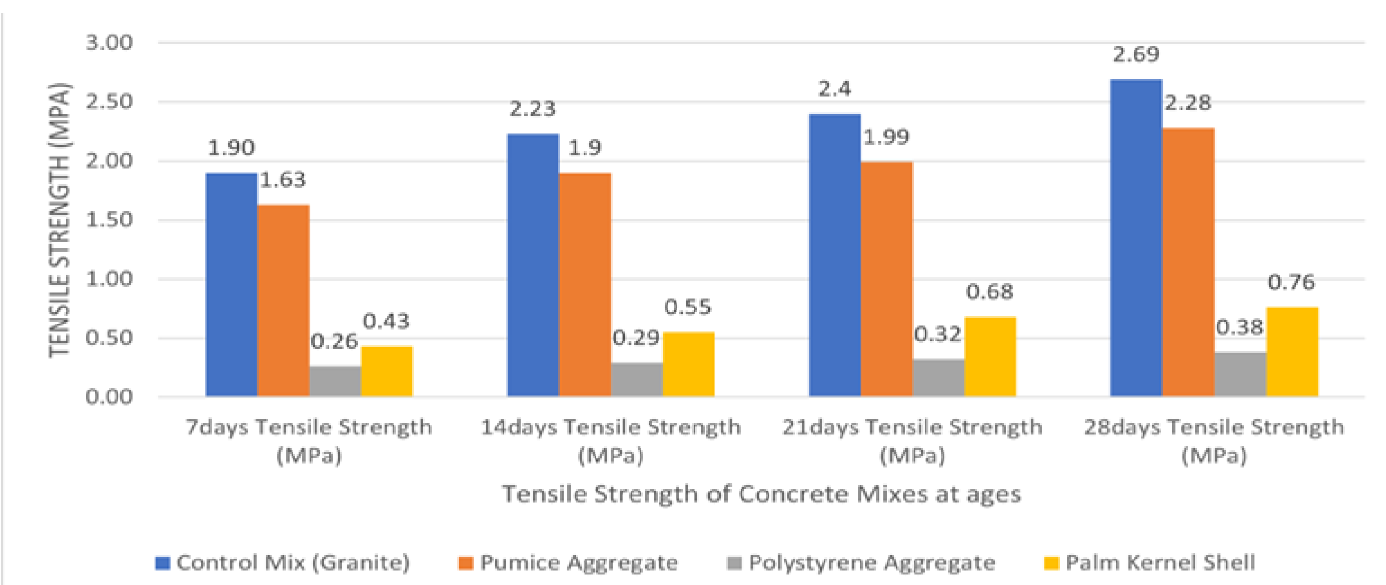

Figure 5. Tensile Strength of Concrete Mixes at Age

lightweight, low-strength applications is highlighted by the strength increasing from 0.43 MPa at 7 days to 0.76 MPa at 28 days. The slow increase in strength indicates that surface treatment or the application of admixtures could enhance palm kernel shell.

Flexural Strength Analysis

The result of flexural strength is shown in figure 6.

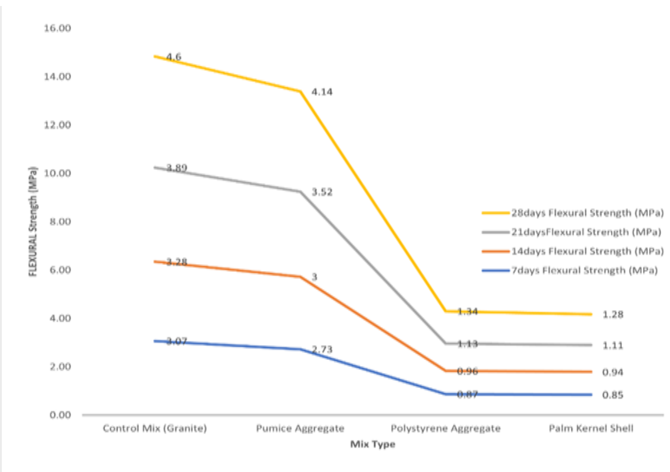

Figure 6. Flexural Strength of Concrete & Lightweight Concrete Samples at Ages

Figure 6 demonstrates that the control batch constantly had the greatest value for flexural strength of all the mix types, beginning at 3.07 MPa at 7 days and increasing to 4.6 MPa at 28 days. The findings highlight granite's remarkable mechanical qualities, specifically its ability to withstand tensile stresses well. Its dense and robust composition sets a standard for comparison with lightweight aggregates.

The flexural strength of the pumice mix was impressive, rising from 2.73 MPa at 7 days to 4.14 MPa at 28 days. Though at somewhat lower values, its strength development roughly resembles that of the control mix. This outcome highlights pumice's potential as a lightweight aggregate for structural applications where weight reduction is preferred without appreciably sacrificing flexural strength. The consistent increase in strength indicates a strong link between the pumice particles and the cement matrix, suggesting that pumice can be a good alternative for load-bearing components in projects that prioritize weight reduction.

Out of all the mixes, polystyrene aggregate had the lowest flexural strength, rising very slightly from 0.87 MPa at 7 days to 1.34 MPa at 28 days. The low strength and lightweight, porous nature of polystyrene, which restricts its load-bearing capacity, are reflected in these statistics. The results show that polystyrene is not suited for structural applications, but it is still perfect for non-structural usage where flexural loads are minimal, including insulating panels, ornamental features, or lightweight partitions. The flexural strength of the palm kernel shell mixture was modest, increasing from 0.85 MPa at 7 days to 1.28 MPa at 28 days. The consistent strength rise indicates its potential in low-strength or non-load-bearing structural applications, even if the values are much lower than those of the control mix or pumice aggregate. The findings demonstrate the potential of palm kernel shells as an economical and sustainable substitute for lightweight concrete, especially in regions where they are readily available.

Water Absorption Analysis

The water absorption is shown in figure 7.

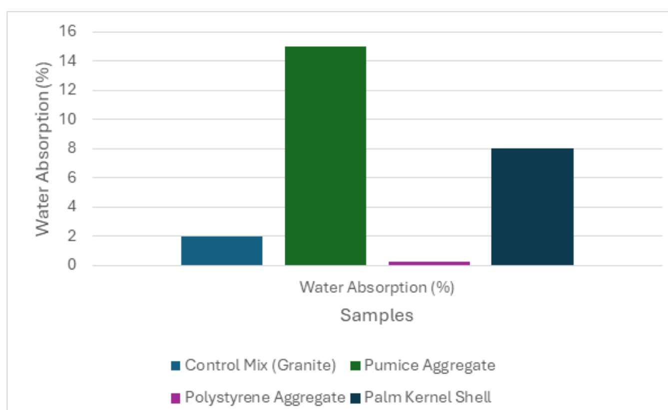

Figure 7: The results, showing water absorption rate of each mix

The control mix with granite had a density of 2%, as illustrated by Figure 7, demonstrating its durability and strength. The high porosity of pumice aggregate, which makes it ideal for lightweight concrete but raises water requirements and may shorten durability, was demonstrated by its 15% percentage. Excellent moisture resistance was demonstrated by the polystyrene aggregate's 0.3% absorption; nevertheless, strength may be compromised by its weak bond with cement paste. The reasonable figure of 8% for palm kernel shell indicates its promise as a sustainable lightweight aggregate; nonetheless, mix changes are required to control porosity. In general, pumice and palm kernel shell are appropriate when reduced density is favored, whereas granite and polystyrene are advantageous for strength and durability.

Conclusion

The following conclusions are drawn from the study: The bulk density test revealed that substituting granite with lightweight aggregates substantially lowers the average density of concrete. The control specimens had the highest density, which indicated strength and durability. Lightweight aggregates generated lower densities, which improved sustainability and insulation but necessitated performance improvements to overcome strength and durability restrictions.

The compressive strength test revealed that the control samples exceeded all other mixtures. Concrete with pumice demonstrated the highest strength among lightweight aggregates, indicating structural potential. Palm kernel shell performed moderately, whereas polystyrene was the poorest, indicating applicability primarily for non-structural or insulating applications.

The control blend demonstrated higher tensile strength and durability. Pumice had good tensile strength but significant absorption, palm kernel shell was moderate, and polystyrene had little absorption but the weakest structural strength, making it suitable for non-structural or insulating uses. The control samples had minimum absorption and the best durability. Pumice's high porosity allows for lightweight use but lowers durability. Polystyrene withstood moisture but bonded poorly, whereas palm kernel shell was mild, necessitating changes for sustainable lightweight concrete.

Recommendations

Pumice is recommended for lightweight concrete applications requiring a balance of weight reduction and strength, such as non-load-bearing walls, waffle slabs, and lightweight partitions.
Polystyrene is appropriate for applications where strength is not an issue, such as insulation boards, soundproofing panels, or lightweight fillers.

Palm kernel shell is ideal for lightweight concrete in applications that require moderate strength, such as walkways, and non-load bearing structural components.

Granite remains the greatest alternative for high-strength applications, and it is recommended for structural parts like beams, columns, and foundations that require a high strength grade of concrete.

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