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Optimal Dosage of Pumice in Lightweight Aggregate based Concrete

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Abstract

Lightweight concrete (LWC) is a pioneering solution in the construction sector, characterized by its unique composition and versatile applications. Engineered with lightweight aggregates and additives, LWC achieves a significant reduction in dry density compared to conventional concrete, making it 23% to 87% lighter, with densities ranging from 300 to 1,840 kg/m³. This reduced weight makes LWC ideal for projects requiring load minimization, such as high-rise buildings and prefabricated elements. A good aggregate is crucial for optimal properties in both fresh and hardened concrete. Pumice stone, a volcanic rock, is often chosen as a replacement for coarse aggregate. Its natural lightness, due to gas escaping from molten lava, makes pumice a strong yet lightweight material suitable for LWC. Additionally, its porous nature can improve the thermal insulation properties of concrete, making buildings more energy-efficient. This investigation focuses on using pumice lightweight aggregate as a partial substitute for aggregates in LWC production, advancing lightweight construction methods. In this study, identification of optimal dosage of pumice lightweight aggregate in concrete was undergone depending on the 28days compressive strength. Lightweight aggregate concrete for M30 and M50 grades, with pumice incorporated at 20%, 40%, and 60% replacement levels of coarse aggregate was done to fix the optimal pumice dosage. Also, split tensile strength of cylindrical specimens and flexural test of prism specimens for obtaining optimal dosage was carried out. The properties such as compressive strength, split tensile strength and modulus of rupture were studied. Overall, the pumice aggregate showed good characteristic for replacing normal coarse aggregate for producing structural lightweight aggregate concrete.

Keywords: Lightweight concrete, pumice coarse aggregate, compressive strength, split tensile strength, modulus of rupture.

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INTRODUCTION

Lightweight concrete (LWC) is becoming a cutting-edge solution in the building industry because of its unique composition and broad range of applications. Engineered by incorporating lightweight aggregates and supplementary additives, LWC achieves a significant reduction in dry density compared to conventional concrete blends [1]. With densities between 300 and 1,840 kg/m³, this decrease yields a material that can be up to 87% lighter than conventional concrete. Due to its significant weight reduction, LWC is especially well-suited for situations where reducing structural load is crucial, such as high-rise buildings, prefabricated concrete elements, bridge decks and overpasses, seismic zone construction and prefabricated components [2].

A key factor in achieving the desired properties in both fresh and hardened concrete is the selection of appropriate aggregates. Pumice stone, a natural lightweight volcanic rock, is an ideal replacement for coarse aggregate in LWC due to its inherent lightness and strength [3]. Formed from the rapid cooling and depressurization of molten lava, pumice is characterized by its porous structure, which contributes to its low density [4]. When used in concrete, pumice aggregates effectively address common challenges in construction, including weight reduction, improved thermal insulation, and enhanced sound absorption. Additionally, empirical evidence has shown that pumice concrete maintains structural integrity over long periods, particularly in preserving the strength of embedded steel reinforcements, making it a durable choice for various structural applications [5].

This study investigates the effects of using pumice lightweight aggregate as a partial replacement for conventional coarse aggregates in M30 and M50 concrete mixes. A series of tests were conducted to assess the impact of pumice aggregate replacement on the mechanical properties of the concrete. The compressive strength test was performed to evaluate the ability of the concrete to withstand loads without failure, which is crucial for assessing the structural integrity of the material. Additionally, split tensile strength tests were carried out to determine the concrete's resistance to tensile stresses, a critical factor in preventing cracking and ensuring long-term durability. The modulus of rupture test was also conducted to measure the flexural strength of the concrete, which is essential for understanding its performance under bending loads.

The choice of pumice lightweight aggregate for this study was motivated by its potential to significantly reduce the weight of concrete while still providing adequate strength for structural use. By examining the effects of various levels of pumice aggregate replacement on different grades of concrete, this research aims to identify optimal mix proportions that maximize the benefits of weight reduction while maintaining the necessary mechanical properties. The findings of this study could offer valuable insights for the development of more efficient, sustainable, and resilient construction materials tailored to the evolving needs of the building industry.

LITERATURE

In a study on M20 grade concrete, researchers replaced conventional coarse aggregate with lightweight pumice aggregate and substituted cement with silica fume at varying percentages (0%, 5%, 8%, 10%, 15%, and 20%). They found that compressive strength increased with up to 10% silica fume replacement, after which it declined. Similar trends were observed in cylinder compressive strength, split tensile strength, flexural strength, and slab moment carrying capacity. Concrete with 100% pumice content exhibited a compressive strength of 8.73 MPa. Increased pumice content resulted in greater deflections in beams and slabs. The study concluded that pumice lightweight aggregate was comparable to other manufactured aggregates like cold bonded and sintered artificial aggregates [6].

In another study, Ordinary Portland cement of 43 grade (IS 12269–1987) was used as a common binding material, and fine aggregate (M-Sand conforming to IS 383–1970) filled voids between coarse aggregates. Coarse aggregate (gravel) met IS 383–1970 standards, while pumice, a natural lightweight aggregate, required soaking for 24 hours due to high-water absorption. Water, conforming to IS-456–2000, was critical for mixing, and Conplast SP430, a superplasticizer, enhanced workability. The M30 grade concrete mix (IS10262-2009) showed optimal properties with 50% pumice replacement. Increasing pumice aggregate decreased concrete density, creating lightweight aggregate concrete, and could replace natural aggregate to reduce concrete self-weight. Pumice's high porosity required superplasticizers due to increased water absorption. Optimal compressive, split tensile, and flexural strengths were achieved at 50% pumice replacement, with higher replacements decreasing strengths. This concrete was suitable for non-load-bearing wall panels in precast buildings, lintels, sunshades, partition walls, and earthquake-resistant structures [7].

In an investigation, Ordinary Portland Cement (53 Grade) was used, with river sand and both normal and pumice coarse aggregates. The mix design, based on IS:10262:2009, had a 1:1.3:2.33 ratio. Control concrete used normal aggregates, while lightweight concrete (LWC) replaced them with pre-wetted pumice. Fresh concrete properties showed higher slump and flow values for LWC. Hardened properties included tests at 7 and 28 days, meeting IS standards. LWC had a 32% lower density, 56% lower compressive strength, but similar tensile strength compared to conventional concrete. It showed 17% reduced acid resistance and 16% lower thermal resistance. These findings suggest that pumice concrete is suitable for lightweight, earthquake-resistant, and thermally insulating structures [8].

In the past construction scenario, concerns grew over escalating tool costs, prompting a focus on cost-effective aggregate over cement in concrete production. Coarse aggregates were foundational in concrete formulations. This study investigated lightweight aggregate concrete (LWAC) beams under two-point bending, contrasting them with normal weight concrete (NWC) beams. Lightweight aggregates, including pumice and palm oil shell (POS), replaced coarse aggregates at varying levels (10% and 50%). Testing approximately 40 samples, including cube specimens and RC beams cured for 28 days, revealed POS exhibited superior strength compared to pumice, affirming its suitability for structural lightweight concrete. LWAC demonstrated slightly lower compressive strength (3.6% to 5.2% less than NWC) but exhibited comparable behavior otherwise, with higher strains attributed to a lower elasticity modulus causing greater deformation [9].

MATERIALS AND METHODS

Materials Used for Experimental Study

The material properties for the ingredients used are shown in Table 1 and the physical properties of pumice coarse aggregates are shown in Table 2.

a. *Cement:* The cement utilized in this study was 53 Grade Ordinary Portland cement conforming to IS: 12269-2013 [10]. It had a specific gravity of 3.1, with initial and final setting times of 40 minutes and 600 minutes, respectively.
b. *Fine Aggregate (FA):* The fine aggregate used in this study complied with Zone-2 standards as per IS: 383-2002 [11]. It had specific gravity 2.8, bulk density 1450 kg/m^3, water absorption: 0.79% and fineness modulus 3.14.
c. *Coarse Aggregate (CA):* Coarse aggregates used in present study was of 20 mm nominal size which was well graded aggregate, according to IS: 383-2002 [11]. It had specific gravity 2.8, bulk density 1500 kg/m^3, fineness modulus of coarse aggregates 7.7, water absorption 0.6%, crushing strength 40N/mm^2 and impact strength 31%.
d. *Pumice Coarse Aggregate (PCA):* the pumice lightweight coarse aggregate used was 20mm nominal size and was well graded aggregate. The specific gravity 2.1, Bulk Density 700 kg/m^3, fineness modulus of coarse aggregates 7.25, water absorption 40%, crushing strength 10N/mm^2 and impact strength 25% (Figure 1).

Table 1. Material Properties of Ingredients Used for Control Concrete.

Ingredient	**Property**	
Cement	Specific gravity	3.14
	Normal consistency	29.50%
	Specific gravity	2.8
Fine Aggregate (FA)	Bulk density	1450 kg/m^3
	Fineness Modulus	3.14
	Water absorption	0.79%
	Specific gravity	2.8
	Bulk density	1500 kg/m^3
Coarse Aggregate (CA)	Fineness modulus	7.7
	Water absorption	0.60%
	Crushing strength	40N/mm^2
	Impact strength	31%

Table 2. Physical properties of pumice coarse aggregates.

Property	
Specific gravity	2.1
Bulk Density	700 kg/m^3
Fineness Modulus	7.25

Water absorption	40%
Crushing strength	$10N/mm^2$
Impact strength	25%

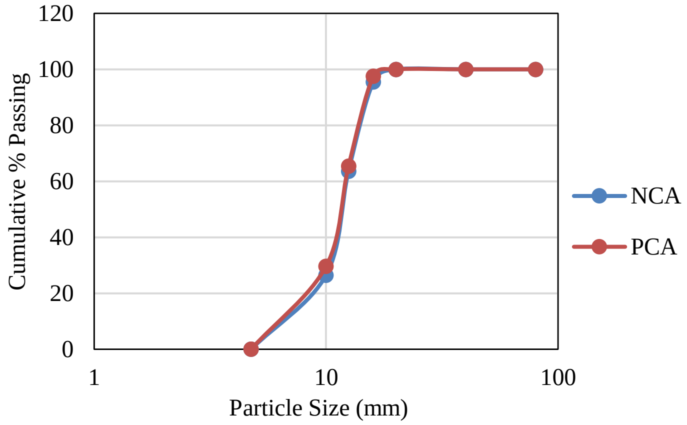

Figure 1. Particle size distribution of Normal Coarse Aggregate (NCA) and Pumice Coarse Aggregate (PCA.

a. *Water:* For this study, potable water was used for mixing and curing the concrete specimens.
b. *Superplasticizer (SP):* In the present study, a polycarboxylate ether-based high-range water reducer (HRWR) confirming to ASTM C494 [12] aided as the superplasticizer. This admixture was used to enhance the workability of concrete mixes by allowing for lower water-cement ratios.

METHODOLOGY

To ensure the research is conducted efficiently and systematically, it was essential to carefully plan and outline the various stages that will serve as a roadmap for the study. Each phase of the process needed to be clearly defined and followed to maintain organization and coherence throughout the research. The detailed stages of the research are depicted in Figure 2, which provides a visual representation of the steps involved.

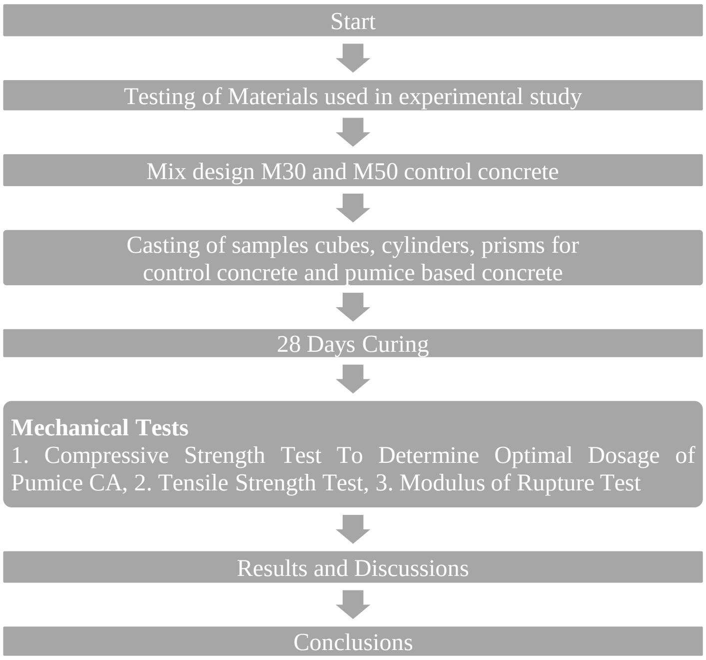

Figure 2. Flowchart of the Methodology Implemented.

EXPERIMENTAL RECORD

Mix Proportion

Mix design was calculated for M30 and M50 grade concrete using IS 10262: 2019 Concrete Mix Proportioning Guidelines [13]. The details of mix proportions are presented in Table 3. Superplasticizer used was 1% of cement weight. For M30 grade and M50 grade concrete slump achieved through slump cone test was 120mm and 125mm respectively.

For the M30 and M50 concrete mixes, the standard mixtures without any pumice replacement are mentioned as Control Concrete (CC). Various replacement percentages of Normal Coarse Aggregate (NCA) with lightweight Pumice Coarse Aggregate (PCA) in the M30 and M50 concrete mixes were tested at 20%, 40%, 60%, 80%, and 100%.

Table 3. Mix proportions of 30 MPa and 50 MPa grade control concrete.

Mix	Cement	FA (kg/m^3)	CA (kg/m^3)	Water (kg/m^3)	W/C Ratio	SP (kg/m^3)
30 MPa	413	678	1154	186	0.45	4.13
50 MPa	429	654	981	161	0.26	4.29

Compressive Strength Test on Control Concrete and Lightweight Pumice Aggregate Concrete

Three samples of cube 150x150x150mm size were casted for each M30 and M50 control concrete. Also, three samples of cube 150x150x150mm size were casted for each percentage replacement of pumice coarse aggregate. The optimal dosage of lightweight Pumice Coarse Aggregate (PCA) for different grades of concrete (M30 & M50) was determined based on the compressive strength test as shown in Table 4.

Table 4. Details of control concrete and pumice aggregate concrete.

Designation	Mix Content
M30	M30 Control Concrete (0% CA replaced with Pumice)
M30-PA20	M30 mix - 20% CA replaced with Pumice
M30-PA40	M30 mix - 40% CA replaced with Pumice
M30-PA60	M30 mix - 60% CA replaced with Pumice
M30-PA80	M30 mix - 80% CA replaced with Pumice
M30-PA100	M30 mix - 100% CA replaced with Pumice
M50	M50 Control Concrete (0% CA replaced with Pumice)
M50-PA20	M50 mix - 20% CA replaced with Pumice
M50-PA40	M50 mix - 40% CA replaced with Pumice
M50-PA60	M50 mix - 60% CA replaced with Pumice
M50-PA80	M50 mix - 80% CA replaced with Pumice
M50-PA100	M50 mix - 100% CA replaced with Pumice

It was observed that as the replacement of pumice increased, the compressive strength of concrete decreased. Details are as mentioned in Figure 3 (a) and Figure 3 (b).

The compressive strength at 28 days for M30 and M50 concrete mixes with various levels of pumice coarse aggregate replacement (20%, 40%, 60%, 80%, and 100%). For the standard M30 mix, the compressive strength was 33.63 MPa. However, with 20% pumice replacement, M30-PA20 mix strength reduced to 28.30 MPa, representing a 15.8% decrease. At 40% replacement, M30-PA40 mix strength further dropped to 25.04 MPa, marking a 25.5% reduction. With 60% pumice, M30-PA60 mix strength declined to 19.85 MPa, showing a 40.9% decrease. At 80% and 100% replacement, M30-PA80 and M30-PA100 mixes compressive strength fell to 14.37 MPa and 10.37 MPa, reflecting 57.3% and 69.2% reductions, respectively. Similarly, for the M50 mix, the initial compressive strength was 53.19

MPa. With 20% pumice replacement, M50-PA20 mix strength dropped to 47.85 MPa, representing a 10.0% decrease. At 40% replacement, M50-PA40 mix strength decreased to 45.04 MPa, indicating a 15.3% reduction. With 60% pumice, M50-PA60 mix strength further fell to 38.81 MPa, marking a 27.0% decrease. At 80% and 100% replacement, M50-PA80 and M50-PA100 mixes compressive strength decreased to 29.19 MPa and 19.85 MPa, showing 45.1% and 62.7% reductions, respectively. The dosage for both M30 and M50 concrete, where the reduction in strength was still within acceptable limits, appeared to be at the 20% replacement level. The 40% replacement level leads to a more substantial reduction in strength compared to 20% replacement. However, the reduction is not as severe as at higher levels (60% and above), and the strength remains relatively higher. Thus, a 40% pumice replacement was chosen as optimal for M30 concrete in moderate-strength applications and viable for M50 concrete in scenarios where slightly lower but still substantial strength was acceptable. Given these findings, the 40% pumice replacement level was selected for further testing to evaluate split tensile strength test on cylinder specimens and modulus of rupture tests on prism specimens. The strength levels at this replacement percentage, particularly for M50, suggested that it might be a viable option when seeking to balance strength with the benefits of using pumice as a lighter aggregate.

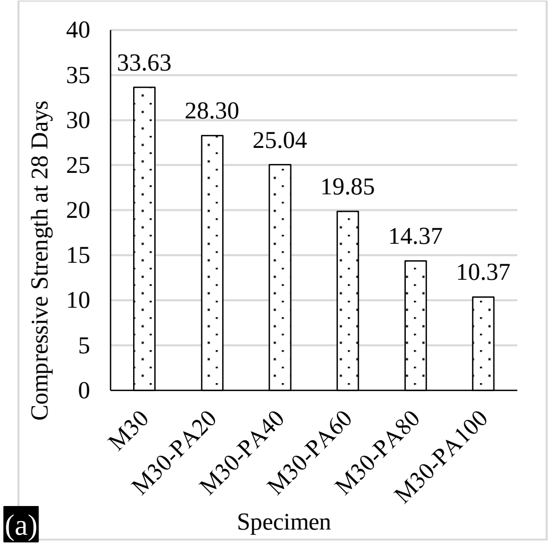

Figure 3. (a) Compressive Strength at 28Days for Different M30 concrete

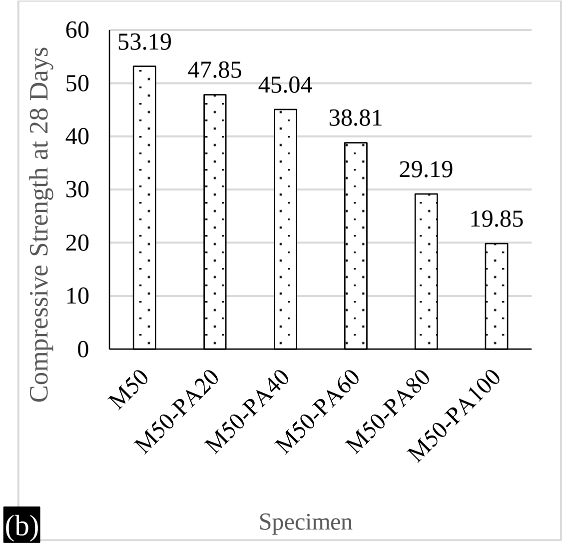

Figure 3. (b) - Compressive Strength at 28Days for Different M50 concrete

Split Tensile Strength on Control Concrete and Optimal Dosage Pumice Aggregate Concrete

The split tensile strength test results demonstrated that both the M30 and M50 concrete mixes experienced a reduction in tensile strength when pumice coarse aggregate was used as a replacement. For the M30 concrete, the split tensile strength was initially measured at 3.54 MPa (Figure 4a). However, when 40% of the coarse aggregate was replaced with pumice, M30-PA40 mix tensile strength significantly dropped to 1.42 MPa, representing a 59.9% reduction. Similarly, the M50 concrete, which had an initial tensile strength of 3.82 MPa, saw a decrease to 1.84 MPa for M50-PA40 with the same 40% pumice replacement, reflecting a 51.8% reduction. The results indicated that the tensile strength of both concrete grades was adversely affected by the inclusion of pumice, with M30 showing a slightly higher percentage reduction compared to M50 (Figure 4b).

Modulus of Rupture Test on Control Concrete and Optimal Dosage Pumice Aggregate Concrete

Modulus of rupture test was conducted on concrete prism specimens as shown in Figure 5 (a). The experimental results for the modulus of rupture of prisms indicated distinct differences among the various specimens. As per Figure 5 (b), for the standard M30 concrete, the modulus of rupture was 3.03 MPa. When 40% of coarse aggregate was replaced with pumice M30-PA40, the modulus of rupture decreased to 2.58 MPa, indicating a reduction in flexural strength. Similarly, for the M50 concrete, the modulus of rupture was higher at 3.29 MPa. However, with a 40% pumice replacement M50-PA40, the modulus of rupture decreased to 2.70 MPa. These findings demonstrate that while the use of pumice aggregate can contribute to weight reduction, it also affects the mechanical properties, particularly in higher-strength mixes like M50. This emphasizes the need to carefully balance the proportions of pumice to achieve both efficiency and resilience in construction materials.

Figure 4. (a) – Split Tensile Strength on M30 Concrete Mix Cylindrical Specimen

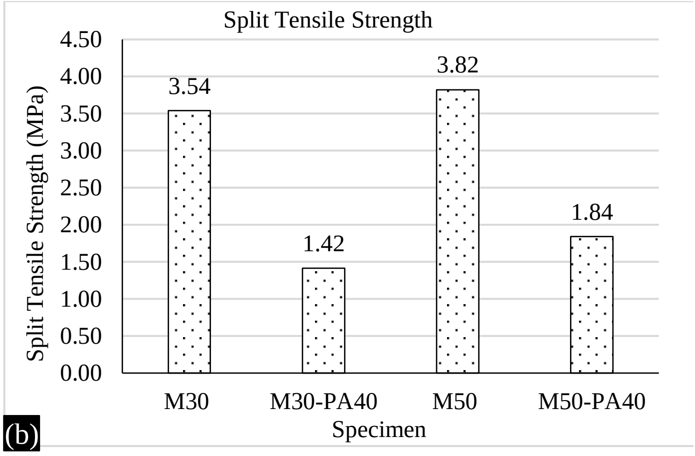

Figure 4. (b) – Split Tensile Strength at 28Days for Different M30 and M50 concrete Mix.

Figure 5. (a) – Arrangement of universal testing machine with prism centred for loading.

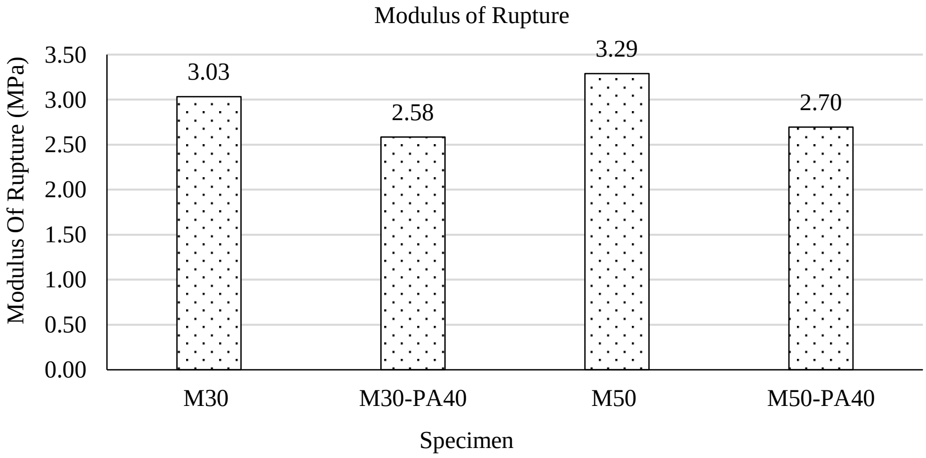

Figure 5. (b) Modulus of Rupture at 28Days for Different M30 and M50 concrete Mix.

RESULTS AND DISCUSSIONS

In compressive strength test, the results showed that both M30 and M50 concrete mixes experienced a reduction in compressive strength with increasing levels of pumice coarse aggregate replacement. For the M30 mix, the compressive strength decreased from 33.63 MPa in the control sample M30 to 25.04 MPa for M30-PA40 at 40% pumice replacement, representing a 25.5% reduction. Similarly, the M50 mix saw a decrease from 53.19 MPa to 45.04 MPa for M50-PA40 at the same 40% replacement level, a 15.3% reduction. While the 20% replacement level resulted in a less significant strength reduction, the 40% replacement still maintained a relatively high compressive strength, particularly in the M50 mix, suggesting that it could be considered an optimal dosage for certain applications where a balance between strength and the benefits of pumice aggregate is desired. However, beyond 40% replacement, the strength reduction became more pronounced, indicating that higher levels of pumice replacement could compromise the structural integrity of the concrete. Thus, while 20% replacement is ideal for minimizing strength loss, 40% replacement could still be considered optimal if a slight reduction in strength is permissible. On a commercial scale, using pumice as a partial replacement for coarse aggregates can offer several advantages. For instance, pumice is a lightweight material that can reduce the overall weight of concrete structures, leading to cost savings in transportation and construction. Additionally, the lower density of pumice can improve the thermal insulation properties of the concrete, making it more energy-efficient. An example of its application could be in the construction of high-rise buildings, where the reduced weight of the concrete would lessen the load on the foundation and support structures, potentially allowing for slimmer columns and beams, which can increase usable space and reduce material costs. Furthermore, using pumice can contribute to the sustainability of construction practices by reducing the reliance on natural aggregates and promoting the use of more eco-friendly materials. While the slight reduction in compressive strength at a 40% replacement level might be permissible for certain applications, it is important to carefully consider the structural requirements and desired performance outcomes when determining the optimal mix proportions.

The results of the split tensile strength tests revealed a significant reduction in strength for both M30 and M50 concrete mixes when 40% of the coarse aggregate was replaced with pumice. The M30 concrete initially exhibited a split tensile strength of 3.54 MPa, which decreased to 1.42 MPa for M30-PA40 with 40% pumice replacement, indicating a 59.9% reduction. Similarly, the M50 concrete's split tensile strength dropped from 3.82 MPa to 1.84 MPa for M50-PA40 with the same level of replacement, representing a 51.8% reduction. The substantial decrease in split tensile strength observed in both M30 and M50 mixes with pumice replacement highlights the material's impact on the tensile properties of concrete. The M30 mix showed a slightly higher percentage reduction compared to the M50 mix, suggesting that the tensile strength of lower-grade concrete may be more sensitive to the replacement of traditional coarse aggregates with pumice. Despite the potential benefits of using pumice, such as reduced weight and improved thermal properties, the significant reduction in tensile strength raises concerns about its suitability in structural applications where tensile performance is critical. However, the reduction in tensile strength suggested that pumice-enhanced concrete may require supplementation with additional materials, such as reinforcing fibers, to ensure that tensile strength meets structural requirements. These considerations are crucial for optimizing the balance between sustainability and performance in concrete applications.

The results showed a notable reduction in the modulus of rupture for both M30 and M50 concrete mixes with pumice replacing 40% of the coarse aggregate. The modulus of rupture for the M30 mix decreased from 3.03 MPa in the control sample to 2.58 MPa for M30-PA40, marking a reduction of about 14.85%. Similarly, the M50 mix's modulus of rupture fell from 3.29 MPa to 2.70 MPa for M50-PA40, a reduction of approximately 17.93%. This decline was attributed to the porous and weaker nature of pumice compared to traditional aggregates, which lowered the tensile strength of the concrete. The greater reduction in the M50 mix indicated that higher-strength concretes are more sensitive to pumice's weakening effects. Despite this, the modulus of rupture with 40% pumice replacement remained relatively high, suggesting its viability for applications where slight tensile strength reduction is acceptable. Incorporating fibers such as steel, polypropylene, or glass could enhance tensile properties and crack resistance, compensating for the strength loss due to pumice replacement. In terms of structural behaviour, concrete with pumice aggregate can be beneficial in applications where weight reduction is a priority without a critical need for maximum tensile strength, such as in non-load-bearing elements or precast concrete products. For instance, in the construction of a multi-story building, using a concrete mix with 40% pumice replacement for non-load-bearing walls can reduce the overall weight of the building, leading to lower material costs and potentially smaller and less expensive structural supports. This approach can result in more sustainable and efficient construction while maintaining adequate performance for the intended application.

CONCLUSION

The following conclusions are drawn from the study's findings and experimental investigation.

- Compressive strength tests exhibited that increasing pumice aggregate replacement decreased strength in both M30 and M50 concrete mixes. A 40% replacement level was found to be optimal, as it maintained relatively high compressive strength, with the M50 mix effectively balancing strength and the benefits of pumice aggregate for producing structural lightweight aggregate concrete.
- Split tensile strength tests unveiled a significant reduction with 40% pumice replacement: M30-PA40 decreased by 59.9% and M50-PA40 by 51.8%. This underscores the need to consider fibers to maintain adequate tensile strength, especially for M30 concrete, which is more affected by pumice replacement.
- The modulus of rupture tests revealed a reduction of about 14.85% for M30 concrete and 17.93% for M50 concrete with 40% pumice replacement. Despite these reductions, the strength remained sufficiently high, demonstrating the viability of pumice as a replacement material. Further improvements in tensile strength and crack resistance could be achieved by incorporating fibers and reinforcement.

Declaration of Interest

The authors declare that there is no conflict of interest regarding thepublication of this manuscript.

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