

Innovative Lightweight Concrete Incorporating Pumice Stone and Palm Oil Fuel Ash

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DOI: <https://doi.org/10.30880/peat.2025.06.02.010>

Article Info

Received: 26 June 2025

Accepted: 11 August 2025

Available online: 30 October 2025

Keywords

Lightweight concrete, Pumice stone, Palm oil fuel ash, Compressive strength, Water absorption, Split tensile

Abstract

This study investigates the development of sustainable lightweight concrete by integrating Pumice Stone (PS) as a full replacement for conventional coarse aggregates and Palm Oil Fuel Ash (POFA) as a partial cement replacement. PS offers natural lightweight properties, while POFA, a palm oil industry byproduct, contributes valuable pozzolanic activity. A total of 48 concrete specimens were prepared using a Department of Environment (DOE) mix design, with POFA content varied at 0%, 10%, 20%, and 30% by cement weight. Comprehensive testing included compressive strength (ASTM C39), split tensile strength (ASTM C496), and water absorption (ASTM C642) at 7 and 28 days. The results demonstrate that the 10% POFA replacement mix achieved optimal mechanical performance, exhibiting the compressive strength 14.34 MPa and 30% split tensile strength 1.30 MPa, and the 10% POFA mix recorded the lowest water absorption. The 10% POFA mix provided the best overall balance of strength, durability, and reduced density. This study confirms the significant potential of PS and POFA in producing environmentally friendly, structurally efficient, and sustainable lightweight concrete.

1. Introduction

Concrete is vital to modern infrastructure but has a major environmental downside—cement production contributes nearly 8% of global CO₂ emissions [1]. As sustainability becomes a priority, lightweight concrete (LWC) is gaining traction for its reduced self-weight, better thermal performance, and lower transport demands. Pumice stone, a naturally porous volcanic rock, lowers concrete density while improving internal curing and the bond at the interfacial transition zone [2]. Similarly, Palm Oil Fuel Ash (POFA) a silica-rich byproduct from palm oil biomass combustion offers pozzolanic properties that improve strength and durability while managing industrial waste [3]. This study investigates an eco-friendly concrete mix using pumice to fully replace coarse aggregate and varying levels of POFA as partial cement replacement. Tests on compressive strength, tensile strength, and water absorption at 7 and 28 days aim to assess the material's potential in sustainable construction. Integrating PS and POFA not only helps reduce the carbon footprint but also supports circular economy practices by converting waste into valuable resources [4][5].

2. Method

The experimental work employed five key materials: Ordinary Portland Cement (OPC), fine aggregate (river sand), coarse aggregate pumice stone, Palm Oil Fuel Ash (POFA), and clean potable water. OPC Type I was used as the primary binder, complying with BS EN 197-1 standards. Fine aggregate was sourced locally and sieved to pass a

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5 mm mesh, ensuring proper particle gradation. Pumice stone 8–10 mm was collected from a commercial supplier and selected for its low density and porous nature, ideal for lightweight applications. POFA, collected from a local palm oil mill in Bukit Pasir, Johor, was oven-dried at $105 \pm 5^\circ\text{C}$ for 24 hours, sieved through a 300 μm mesh [6]. Partial cement replacement at varying percentages 10%, 20%, and 30% by weight. Tap water free from impurities was used in all mixing and curing stages.

2.1 Mix Proportion

Concrete mix proportions were designed based on the Department of Environment (DOE) method, targeting a concrete grade of 15 MPa. Four mix variations were prepared: a control mix 0% POFA and three mixes with 10%, 20%, and 30% POFA as cement replacement. Pumice stone was used as a full substitute for natural coarse aggregate in all mixes. The water-cement ratio was maintained at 0.55 for cubes and 0.47 for cylinders to ensure consistency and optimal workability. Two sets of specimens were cast which is cubes 150 mm x 150 mm x 150 mm and cylinders 150 mm diameter and 300 mm height as shown in figure 1 and each mix variation produced mix variation produced six cube and cylinder specimens, with equal numbers tested at 7 and 28 days as shown in table 1 and table 2.

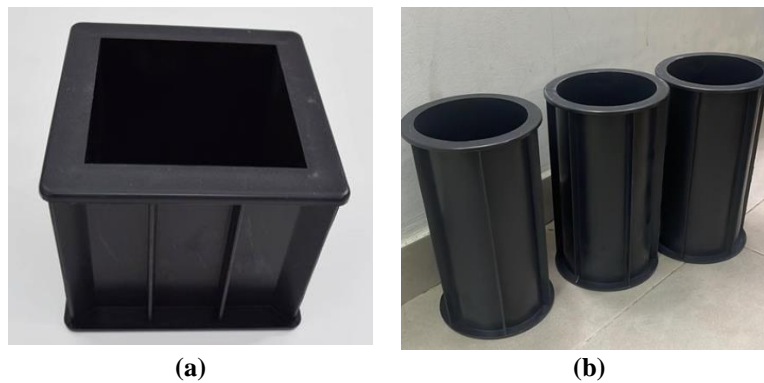


Fig. 1 (a) Cube mould; (b) Cylinder mould

Table 1 Mix design for cube specimens

Percentage of POFA %	Cement (kg/m ³)	POFA (kg/m ³)	Sand (kg/m ³)	Pumice Stone (kg/m ³)	Water (kg/m ³)	7 Days Samples	28 Days samples
0%	400	0	350	400	223	3	3
10%	360	40	350	400	223	3	3
20%	320	80	350	400	223	3	3
30%	280	120	350	400	223	3	3
Total						24	

Table 2 Mix design for cylinder specimens

Percentage of POFA %	Cement (kg/m ³)	POFA (kg/m ³)	Sand (kg/m ³)	Pumice Stone (kg/m ³)	Water (kg/m ³)	7 Days Samples	28 Days Samples
0%	510	0	445	315	240	3	3
10%	459	51	445	315	240	3	3
20%	408	102	445	315	240	3	3
30%	357	153	445	315	240	3	3
Total						24	

2.2 Testing

After 24 hours of casting, all concrete specimens were demoulded and immersed in a curing tank filled with tap water, maintained at an ambient laboratory temperature of approximately $27 \pm 2^\circ\text{C}$. The curing durations were set at 7 and 28 days to ensure adequate hydration and the development of mechanical properties.

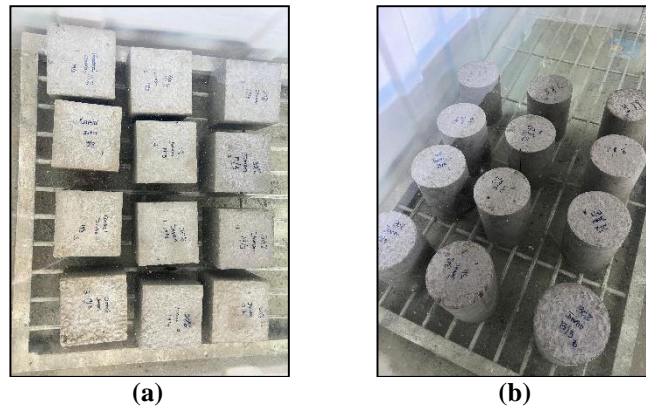


Fig. 2 (a) Cube curing; (b) Cylinder curing

All experimental procedures were conducted in accordance with relevant ASTM standards. The compressive strength test was performed using a hydraulic compression testing machine, following the procedures outlined in ASTM C39/C39M. The split tensile strength test was conducted using the diametral compression method in accordance with ASTM C496/C496M [7]. The water absorption test was carried out based on [8], which involved oven-drying, immersion in water, and subsequent weighing to determine the absorption capacity. All tests were performed at the Concrete Laboratory of Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Campus. The collected data were analyzed and presented using Microsoft Excel to facilitate interpretation and graphical representation.

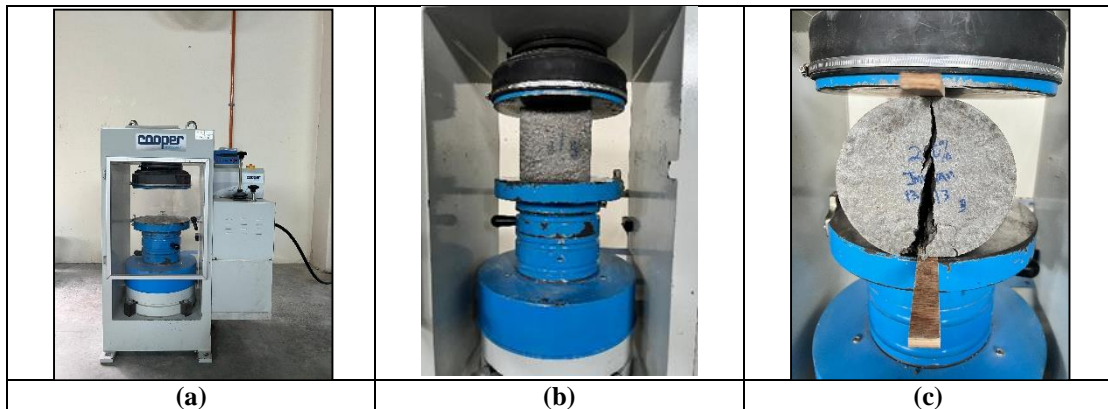


Fig. 3 (a) Hydraulic compression; (b) Compressive strength test; (c) Split tensile test

2.3 Water Absorption Test

After 7–28 days of curing, specimens were oven-dried at 100–110 °C for 24 hour and weighed. Then submerged in water 18–25 °C for 24 hours, removed, surface-dried, and reweighed. Water absorption (%) was calculated per ASTM C642 (2023). as shown in equation 1 where W_s is the saturated weight of the specimen after being immersed in water, and W_d is the dry weight after being oven-dried. The difference between the saturated and dry weights shows how much water has been absorbed, and this value is expressed as a percentage of the dry weight.

$$\text{Water Absorption (\%)} = \left(\frac{W_s - W_d}{W_d} \right) \times 100 \quad (1)$$

2.4 Compressive Strength Test

Compressive strength tests were carried out on cube specimens. As per ASTM C39/C39M [9] and BS EN 1881-116, cubes measured 150 mm × 150 mm × 150 mm. After 7 and 28 days of curing, the cube specimens were surface dried and tested using a compression machine. A uniform load of 0.35 MPa/s was applied until failure, and the

maximum load was used to calculate the compressive strength in MPa. The equation for the compressive strength was shown in equation 2.

$$\text{Compressive Strength (MPa)} = \frac{\text{Maximum Load (N)}}{\text{Cross-section Area (mm}^2\text{)}} \tag{2}$$

2.5 Split Tensile Test

The equation 3 shown the splitting tensile strength, measured in megapascals (MPa), indicates the concrete’s ability to resist tension before cracking. It is calculated using the formula: $\text{Splitting Tensile Strength} = 2P / \pi LD$, where P is the maximum load applied at failure in newtons, L is the length of the cylindrical specimen in millimetres, and D is the diameter. The test was done on cylindrical specimens measuring 150 mm in diameter and 300 mm in height, following ASTM C496. The cured cylinders were placed horizontally in the testing machine, and a continuous load was applied along their vertical diameter until a crack formed and the specimen failed.

$$\text{Splitting Tensile Strength (MPa)} = \frac{2P}{\pi LD} \tag{3}$$

3. Result

Based on the figure 4 showed water absorption decreased from 5.1% in the control mix to 4.5% in the 20% POFA mix, indicating better pore refinement. The 30% POFA mix showed the highest absorption at 5.6%, likely due to excessive ash content increasing porosity. The absorption values were slightly higher as shown in figure 5. The 20% POFA cylinder mix showed improved durability with absorption of approximately 4.9%, while the 30% POFA mix exceeded 5.8%. The pozzolanic contribution of POFA play key roles in controlling water ingress. According to [10], POFA enhances the microstructure by forming additional calcium silicate hydrate (C-S-H), which blocks capillary pores and reduces permeability.

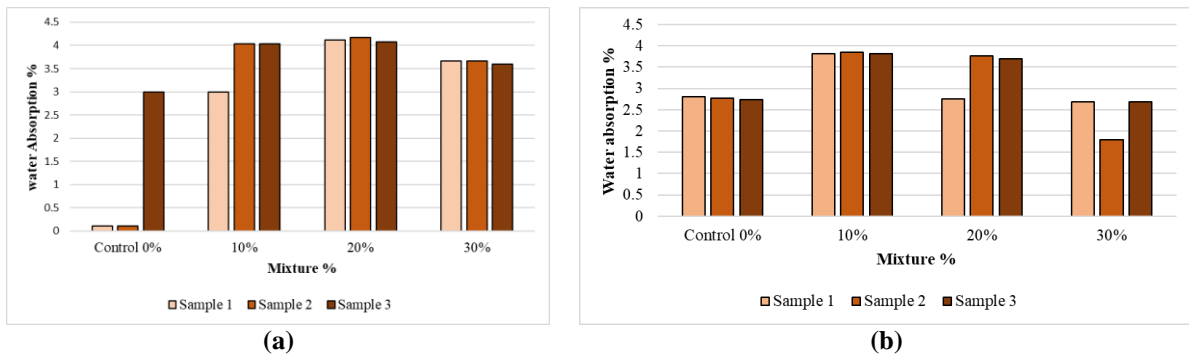


Fig. 4 Water absorption for cube samples (a) 7 days; (b) 28 days

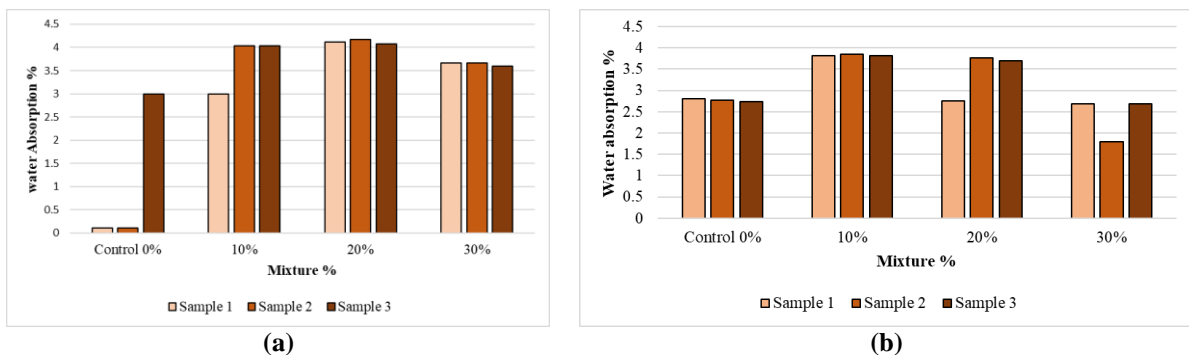


Fig. 5 Water absorption for cylinder samples (a) 7 days; (b) 28 days

According to figure 6 shown the compressive strength results show that adding POFA has a clear impact on the strength of lightweight concrete. At 7 days, the control mix (0% POFA) reached 14.6 MPa, while the 20% POFA mix performed better with 16.5 MPa. By 28 days, all mixes gained strength, with the 20% POFA mix reaching the highest at 19.2 MPa. This improvement is due to the pozzolanic reaction of POFA, which forms more calcium silicate hydrate (C-S-H) and strengthens the concrete [3].

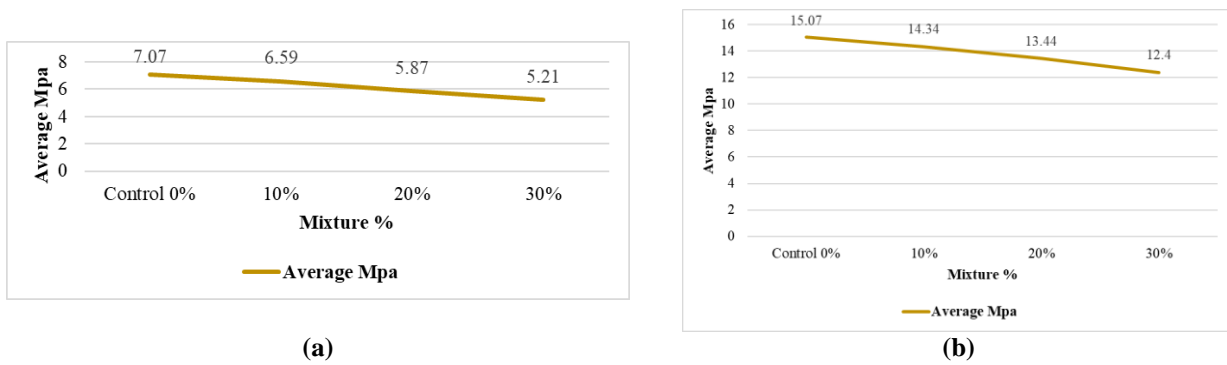


Fig. 6 Compressive strength for cube samples (a) 7 days; (b) 28 days

However, when the POFA content was increased to 30%, the strength dropped to 15.4 MPa at 28 days. This decline is caused by the excess POFA disrupting the cement mix and weakening the overall bond. Similar trends were observed by Adnan [11], where moderate POFA levels improved strength, but too much had the opposite effect. Moreover, using 20% POFA provides the best balance, improving strength while meeting lightweight concrete standards and supporting sustainable construction.

According to figure 7 shown Split tensile strength followed a similar trend to compressive strength but with lower values, as expected due to concrete's weakness in tension. At 7 days, the control mix recorded 1.32 MPa, while the 20% POFA mix reached 1.56 MPa. At 28 days, the 20% POFA mix showed the highest strength at 1.85 MPa, surpassing the control mix at 1.67 MPa.

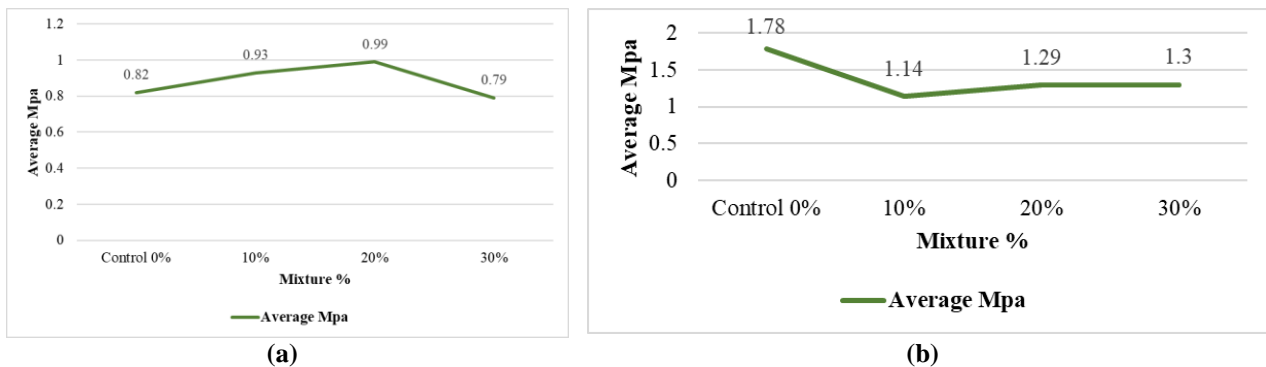


Fig. 7 Tensile Strength for cylinder samples (a) 7 days; (b) 28 days

At 28 days, the split tensile strength for the control mix was 1.67 MPa. The 10% POFA mix increased this slightly to 1.74 MPa. The 20% POFA mix recorded the highest tensile strength at 1.85 MPa. The 30% POFA mix had the lowest value among POFA mixes, measuring 1.61 MPa. The results indicate that tensile strength followed a similar trend to compressive strength [12], where pozzolanic materials and lightweight aggregates improved tensile strength. However, the 30% POFA mix showed a slight drop to 1.61 MPa, suggesting that too much POFA may increase porosity and weaken the concrete. Thus, a 10% POFA replacement appears to provide the best balance for improving both compressive and tensile strength.

4. Conclusion

The incorporation of pumice stone and POFA in lightweight concrete successfully reduced density while maintaining mechanical strength and acceptable durability. The results clearly demonstrated that the integration of these two materials enhances mechanical properties and reduces overall density, contributing to a more sustainable concrete solution. Based on its well-balanced performance, the 10% POFA mix is recommended as the most suitable option for sustainable lightweight applications that are non-structural in nature, such as partitions, pavement blocks, and lightweight wall systems. To ensure its broader application and reliability, future studies should investigate aspects like long-term durability including resistance to chemical attack, shrinkage behavior, and freeze-thaw performance alongside in-depth microstructural evaluation, field-scale performance trials, and cost-efficiency analysis.

Acknowledgement

This author would like to thank the Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, for its support.

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