

An Experimental Investigation of the Mechanical Properties of Lightweight Concrete with Pumice Aggregate and Polypropylene Fibers

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ABSTRACT

This study investigates how adding Polypropylene Fibers (PPF) affects the mechanical properties of structural lightweight concrete. Four mixes with varying fiber contents 0%, 0.5%, 1%, and 1.5% were tested at different curing ages up to 90 days. The results show that PPF significantly improves the Flexural Strength (FS) and Tensile Strength (TS), with a moderate increase in Compressive Strength (CS). The mix containing 1.5% PPF achieved the highest TS, likely due to enhanced microcrack bridging and a denser microstructure. The statistical analysis confirmed that the fiber content strongly influences the strength development, particularly the tensile performance. Overall, incorporating 1%-1.5% PPF appears to be an effective way to enhance the durability, toughness, and structural integrity of lightweight concrete, making it suitable for demanding construction applications.

Keywords-polypropylene fibers; compressive strength; lightweight concrete; fiber-reinforced concrete; sustainable construction; splitting tensile strength; pumice aggregate; flexural strength

I. INTRODUCTION

The use of PPF in lightweight concrete has gained significant attention due to its potential to enhance its strength and durability. Lightweight concrete is favored in construction for its reduced deadload and improved thermal insulation. However, it generally exhibits lower TS and is more susceptible to cracking. Incorporating PPF helps mitigate cracking and improves both the TS and FS [1–6]. This study is the first to conduct a detailed long-term (up to 90 days) evaluation of the mechanical performance of lightweight concrete made with pumice aggregate and varying PPF dosages (0.5% and 1.5%). Prior research has shown that PPF significantly enhances the mechanical behavior of lightweight concrete. Authors in [5] reported that the pretreatment of PPF improves concrete's mechanical properties and microstructure, leading to greater durability and strength. Authors in [13] found that adding PPF to recycled concrete improved both the static and dynamic CS due to better micropore system organization. The integration of PPF also reduces shrinkage in lightweight aggregates and increases the fracture resistance. Authors in [7–9] revealed that higher PPF content decreases the scale-dependence of ductility and lowers the energy needed for crack

propagation, thereby improving toughness. Recycled PPF, especially from single-use face masks, has also been shown to enhance the concrete performance while contributing to waste reduction and sustainable construction practices [10, 11]. Despite these findings, further research is needed to understand how different PPF concentrations affect both the mechanical and shrinkage properties over extended curing periods. This study addresses that gap by examining compressive, flexural, and splitting tensile strengths at 7, 28, 60, and 90 days. While the benefits of PPF in improving strength and degradation resistance are well-documented, more data are needed on its influence over time. Several studies support PPF's effectiveness. Authors in [12, 13] reported notable improvements in the static and impact CS of recycled concrete due to the fiber's nanoscale porosity and structure. Authors in [8] investigated the fracture behavior of PPF-reinforced lightweight aggregate concrete and found that a higher fiber content reduced the influence of the sample size on ductility and fracture energy absorption. Authors in [5, 14] highlighted how the pretreatment of PPF enhances the microstructural properties and long-term durability, indicating promising performance benefits.

A. Research Gap

PPF-reinforced lightweight concrete has attracted considerable academic interest due to its potential to improve the compressive strength, enhance the energy absorption, and reduce shrinkage [15, 16]. However, most existing studies focus only on early-age behavior, typically up to 28 days, leaving a gap in understanding the long-term effects of varying fiber contents, specifically between 0.5% and 1.5% by volume, on the mechanical and durability-related properties beyond 60 and 90 days [17, 18]. While authors in [18, 19] suggest that PPF reduces cracking and refines the micropore structure, these claims often lack sufficient experimental validation, particularly in terms of quantifying the microstructural changes. Although Scanning Electron Microscopy (SEM) has been used to examine fiber-matrix interactions and their effect on FS in lightweight foamed concrete, these investigations rarely consider a range of fiber dosages or extended curing durations. This demonstrates a disconnection between the observed mechanical improvements and their underlying microstructural causes. Additionally, while earlier studies have noted that PPF may reduce the early shrinkage cracking, there is limited experimental evidence showing how varying fiber amounts influence the long-term drying shrinkage or matrix densification, factors that directly affect the concrete durability, such as chloride permeability and water absorption. The lack of such data makes it difficult to identify the optimal fiber dosage for achieving durable, high-performance lightweight concrete.

TABLE I. CEMENT CHEMICAL COMPOSITION AND MAIN COMPONENTS

Oxide compositions	Weight (%)	Threshold of [25]
Lime (CaO)	60.35	-----
Iron oxide (Fe ₂ O ₃)	4.16	-----
Alumina (Al ₂ O ₃)	5.08	-----
Silica (SiO ₂)	20.64	-----
Insoluble residue (IR)	0.86	≤ (1.5)
Magnesia (MgO)	3.86	≤ (5)
Loss on ignition (LOI)	3.21	≤ (4)
Sulfate (SO ₃)	2.67	SO ₃ ≤ 2.8 if C ₃ A > 3.5 SO ₃ ≤ 2.5 if C ₃ A ≤ 3.5
Main compounds of cement		
Tri-calcium silicate (C ₃ S)	41.07	----
Dicalcium silicate (C ₂ S)	27.83	----
Tricalcium aluminate (C ₃ A)	6.43	----
Tetra-calcium aluminate – ferrite (C ₄ AF)	12.64	----
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II. MATERIALS AND METHODS

This research investigates the impact of PPFs on the mechanical properties of lightweight concrete through experiments. The experimental procedure involves selecting

components and mixes, preparing test samples, curing the concrete, and testing both fresh and hardened concrete. Moreover, One-directional Analysis of Variance (ANOVA) was performed to determine the statistical difference of the mechanical performance results of the four concrete mixes. The research involved four specimens of the mix during the curing ages of 7, 28, 60, and 90 days. The statistical computation was performed using Python with a preset significance level of 0.05. Ordinary Portland Cement (CEM I, 42.5R) was employed, according to [25]. Tables I and II demonstrate both the physical and chemical properties of the cement. The number of tested specimens was n=4.

The fine aggregate comprised natural sand with a fineness modulus of 2.6. The sand met the requirements specified in [26] and was free from contaminants. The sand sieve grading and main characteristics complied with [27] and lie in Zone 2. Table III summarizes the physical characteristics and the chemical composition of the selected sand. Table IV displays the grain size distribution of the sand.

TABLE II. PHYSICAL REQUIREMENTS/PROPERTIES OF CEMENT

Physical properties	Weight (%)	Threshold of [25]
Specific surface area (Blaine's approach) (m ² / kg)	349.8	≥ 280
Setting time: initial setting (min)	90	≥ 45 min
Setting time: final setting time	4.42 hr	≤ 10 hr
Soundness by autoclave approach (%)	0.19	≤ 0.80
CS in MPa		
CS (2) day	21.75	≥ 20
CS (28) day	46.63	≥ 42.5

TABLE III. SAND PROPERTIES

Property	values	Limits [26]
Specific gravity	2.6	---
Absorption, %	0.72	---
Density (kg/m ³)	1580	---
Sulphate content, % (SO ₃)	0.343	Maximum 0.5%

TABLE IV. SIEVE ANALYSIS

Sieve size(mm)	% Passing	Requirements of [26]/zone 2
10	100	100
4.75	95.6	90-100
2.36	80	75-100
1.18	78	55-90
0.6	54.4	35-59
0.3	26.3	8-30
0.15	4.7	0-10
Finance modulus (F.M)=2.61		

The pumice complied with [28]. Its physical characteristics and the composition analysis of the pumice are presented in Table V.

TABLE V. PHYSICAL PROPERTIES OF PUMICE

Density (kg/m ³)	656
Hardness (MOHS)	6
Softening point	900
Color	white
Absorption %	28

The Silica Fume (SF) strength activity index records 121% and conforms to [14, 29]. Tables VI and VII provide the engineering data for the SF.

TABLE VI. PHYSICAL VALUES OF SF

Physical properties	Values	Specifications of [29]
Percent accumulated on 0.045 mm (sieve #325)	7	≤ 10
7-Day accelerated pozzolanic activity index using Portland cement	121	≥ 105
Specific surface m ² /g	10	≥ 15

Treated water sourced directly from drinking water systems was used for both the mixing and curing processes to prevent harm to the concrete. Fifty mm-long PPFs with an aspect ratio of 50 were added to the concrete mixes. PPFs possess a TS of 400 MPa and a melting point of about 160 °C. Adding PPF was intended to improve the concrete’s TS and FS. A water-reducing admixture was used to increase the mix’s flowability without altering the water-to-cement (w/c) ratio.

III. MIX DESIGN

Four concrete mixes were prepared: A mix free of fibers and three mixes reinforced with PPF at 0.5%, 1.0% and 1.5% incorporation levels by the weight of cement. The mixed proportions were formulated to achieve the desired CS for structural lightweight concrete. A constant w/c ratio of 0.45 was employed for all the mixes. The design considerations of the mixed proportions were adopted based on [33] and Table VII.

TABLE VII. MIX PROPORTIONS AND DETAILS

Component	Control mix	0.5% PPF	1.0% PPF	1.5% PPF
Cement (kg/m ³)	450	450	450	450
Fine aggregate (kg/m ³)	775	775	775	775
Coarse aggregate (pumice)(kg/m ³)	490	490	490	490
Water (kg/m ³)	166	166	166	166
Superplasticizer (% by weight of cement)	1	1	1	1
PPF (kg/m ³)	0	2	4	6

IV. HARDENED CEMENT TESTS

CS was measured on 100 mm cubes according to [30]. The splitting strength of the specimens was determined using 100 mm × 200 mm cylinders, prepared for testing, as in [31]. Prisms with dimensions of 100 mm × 100 mm × 400 mm were evaluated based on [32]. Using these methods, the data were analyzed to evaluate how different fiber levels affected the mechanical performance of lightweight concrete.

V. RESULTS AND DISCUSSION

The results of testing concrete reinforced with increasing concentrations of PPF are described and analyzed in this chapter, specifically at concentrations of 0.5%, 1%, and 1.5% by cement mass. Changes in the mechanical performance of the

concrete were observed in specific periods of 7, 28, 60, and 90 days following the initial placement. The results are displayed graphically, and the influence of various fiber dosages on the concrete performance is further discussed in [20].

A. Compressive Strength

Figure 1 shows that the CS evolved with curing time for both the control mix (M ref) and the mixes reinforced with PPF. The data demonstrate that the CS improved as the curing time progressed for all mixes.

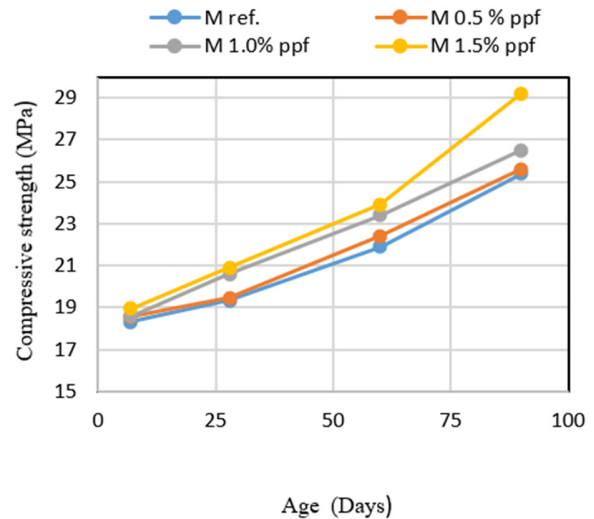


Fig. 1. CS with age.

Adding PPF slightly increased CS compared to the reference mix. The maximum CS was achieved for the M 1.5% PPF mix after 90 days (29.2 MPa), which was 14.96% greater than the values achieved by the control mix. Significant improvements were observed as the age of the specimens increased after the first 28 days of curing. This improvement stems from the ongoing hydration and the fibers’ inhibiting effect on microcrack formation [21].

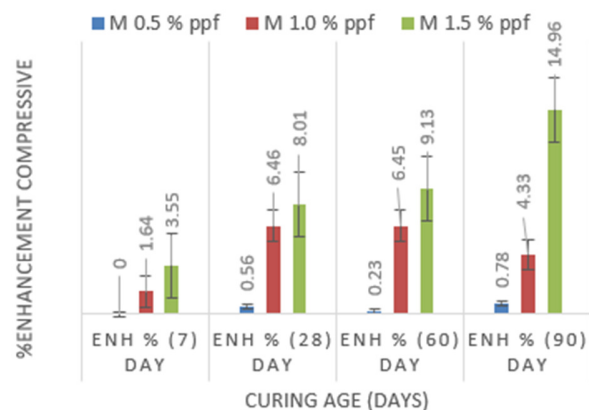


Fig. 2. CS improvement (%) with age.

As observed in Figure 2, the M 1.5% PPF mix exhibits the largest gain in CS after 90 days. The results confirm that PPF improves both the resistance to cracks and the ability to maintain the load after failure occurs. Like other studies, the gains in CS were considerably smaller than the corresponding increases in tensile and flexural performance.

B. Flexural Strength

An enhancement trend in FS was noticed for all mixes during the curing period. The control mix achieved an FS of 4.8 MPa at 90 days, whereas the 1.5% PPF mix achieved 5.9 MPa, representing a 22.92% increase. The addition of fibers increased the material's toughness [22] and ductility, enabling greater energy dissipation during bending, as shown in Figure 3.

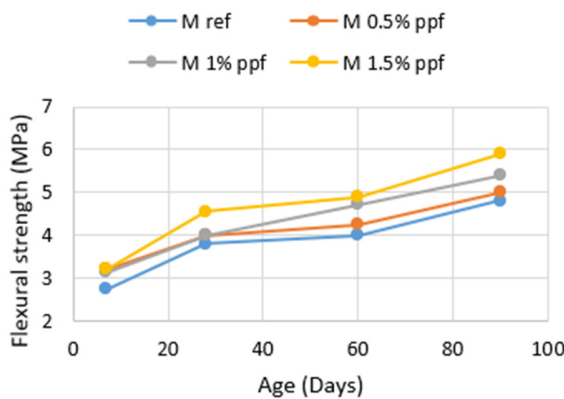


Fig. 3. FS with age.

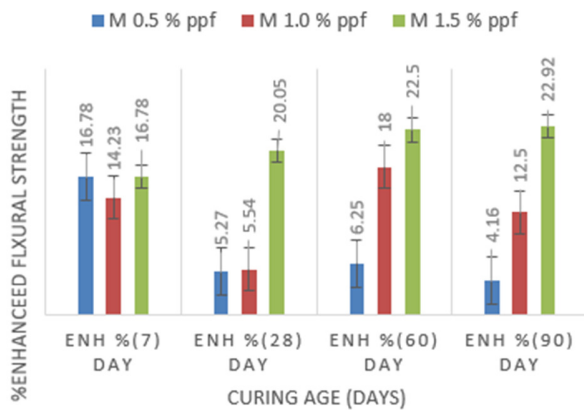


Fig. 4. FS improvement (%) with age.

The improvements in strength for the M 1.5% PPF mix were exceptionally high. It reached 20.05% in 28 days, then increased to 22.92% at the 90-day point. The microstructural observations indicate that, while the fibers indeed bridge and compress the crack through their high stiffness and extension resistance, they also cause microstructural densification around the fiber-matrix junctions, further enhancing the efficiency of the load transfer and overall toughness.

C. Splitting Tensile Strength

PPF significantly enhanced the splitting TS. The M ref mix had a splitting TS of 1.85 MPa after 90 days compared to 2.83 MPa for the M 1.5% PPF mix. This corresponds to a 52.97% improvement. PPF significantly enhanced the tensile performance by influencing the crack growth, as portrayed in Figure 5.

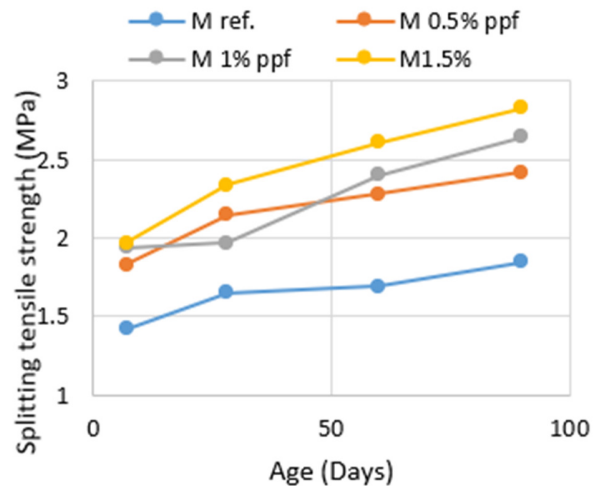


Fig. 5. Splitting TS with age.

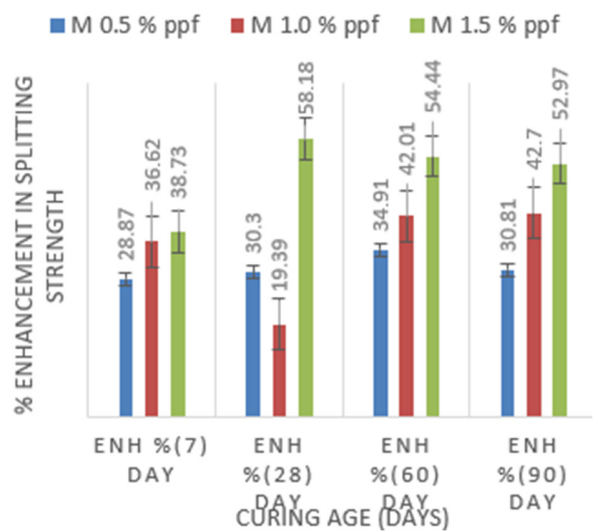


Fig. 6. Splitting TS improvement (%) with age.

As observed in the mechanical tests, the addition of PPF to pumice lightweight concrete significantly enhanced its structural performance during the test of the structural behavior of this material, especially at a fiber dosage of 1.5% by cement weight. The gains in CS, FS, and TS are closely associated with microstructural processes, as confirmed by SEM, and are supported by the literature. Under CS, the improved values, especially in the 1.5% PPF mix, can be attributed to the fiber bridging impact on the pore framework improvement. The analysis of SEM reveals that the fibers prevent the initiation

and growth of microcracks under load, postponing the onset of failure, in addition to the post-peak ability of the sample to support a load. The physical crack growth is impeded by the presence of fibers in the matrix, resulting in a tighter microstructure and lower stress concentration in the cement paste.

One of the key factors contributing to the improved FS of PPF-reinforced lightweight concrete is the micro-level interaction between the fibers and the cementitious matrix. The fibers act as micro-reinforcements, aligning with the developing tensile cracks and resisting their propagation under bending stresses. The SEM images confirmed that the fibers were uniformly distributed and well-anchored within the matrix, exhibiting both mechanical interlock and frictional adhesion. This enhanced bonding leads to a greater energy absorption and increased ductility, particularly at the 1.5% fiber dosage, which also showed the smallest crack widths. In terms of splitting TS, the improvements were most pronounced. The 1.5% PPF mix demonstrated over a 50% increase compared to the control. This can be attributed to the fibers' ability to redirect and disperse tensile stresses across multiple microcracks, preventing the formation of large, singular fractures. The SEM analysis revealed fiber pull-out patterns in specimens subjected to tensile testing, highlighting their role in dissipating energy and arresting the crack growth. Additionally, the fiber-matrix interface appeared denser and exhibited fewer voids, suggesting strong adhesion and effective load transfer under tensile stress. Contrary to the common assumption that fibers merely occupy existing pores or microcracks, the SEM observations showed that PPFs were located not only along cracks, but also within the voids and pores, leading to reduced pore sizes and improved internal packing. This refined microstructure likely contributes to enhanced strength and durability, even though specific durability tests (e.g., permeability or water retention) were not part of this study. In summary, the superior performance of the 1.5% PPF mix can be attributed to several interrelated microstructural mechanisms: crack bridging, pore filling, strong fiber-matrix bonding, and overall pore refinement. These findings align with previous research on high-performance fiber-reinforced concrete and reinforce the effectiveness of PPF in improving both the mechanical and durability-related properties.

In addition to the mechanical improvements, incorporating PPF, especially those sourced from recycled materials offers measurable environmental benefits. A Life Cycle Assessment (LCA) comparing virgin and industrially recycled PPF used in concrete footpaths found that recycled PPF can reduce the environmental impacts by approximately 50% in CO₂ emissions, 65% in phosphate (PO₄) emissions, 29% in water usage, and 78% in oil consumption compared to the virgin PPF production [22]. Another study reported that using recycled PPF instead of steel mesh can result in a 93% reduction in CO₂ emissions, a 97% reduction in PO₄ emissions, and a 99% reduction in water use [23]. These findings support the broader conclusion that recycled PPF not only enhances the mechanical durability and crack resistance, but also significantly lowers the environmental impact. This aligns with reviews indicating that fiber-reinforced concrete can reduce the global warming potential by up to 94%, provided that sustainable fibers and

responsible manufacturing practices are employed [24]. Overall, both virgin and especially recycled PPF have a smaller environmental footprint than traditional polyester fibers, reinforcing the sustainability case made in this study.

D. Statistical Evaluation Using ANOVA

To assess the significance of the differences in mechanical performance among the concrete mixes, a one-way ANOVA was conducted for each strength property. The results showed that the variations in CS ($p = 0.931$) and FS ($p = 0.801$) were not statistically significant at the 95% confidence level. This suggests that, despite the observable trends, particularly the apparent strength gains in the 1.5% PPF mix, these differences cannot be attributed to the fiber content alone. Possible explanations include mix uniformity or variations in curing conditions. In contrast, the splitting TS results yielded a statistically significant difference ($p = 0.016$), indicating that the fiber content had a clear and measurable impact on the tensile resistance. These findings underscore the importance of fiber dosage in enhancing the tensile performance, while also highlighting the need for further investigation into compressive and flexural improvements. Additional studies with larger sample sizes or more detailed microstructural analysis may be required to validate those effects. Each test included four specimens per mix and curing age, with standard deviations represented through error bars. These methods were implemented to minimize the influence of random variation and ensure the reliability of the results.

VI. CONCLUSIONS

The results presented herein offer experimental information on the long-term behavior of lightweight concrete with Polypropylene Fibers (PPF) and pumice aggregate, which can serve as a guide for determining the most appropriate dosage of fiber in sustainable constructions. The main findings are:

- The mechanical behavior of lightweight concrete reinforced with different levels of PPF (0.5%, 1% and 1.5%) was investigated and compared to a control mix without any PPFs. Tests were performed to determine the mechanical properties of fresh and hardened concrete at various ages: Compressive Strength (CS) [30], Flexural Strength (FS) [32], and splitting Tensile Strength (TS) [31] at ages of 7, 28, 60, and 90 days.
- The experiments exhibited that adding PPF enhanced the mechanical behavior of lightweight concrete, especially for properties related to TS. Adding 1.5% PPFs resulted in the greatest increase in splitting TS, achieving 58.18% better performance at 28 days compared to the mix without fibers. For the same formula, the flexibility and resistance to bending improved by 22.92% after 90 days, whereas the maximum CS rose by 14.96% around the same time.
- This trend indicates that the addition of PPF continuously improves both the early-age and long-term mechanical properties; however, the greatest CS gains appear to be limited at a fiber dosage of 1%. This suggests that an ideal fiber concentration can optimize the balance between enhanced strength and workability.

Positive relationships were observed between the non-empirical use of PPF and the performance of concrete. However, the Analysis of Variance (ANOVA) revealed that, although the CS and FS increased with the increase in the PPF content, only the splitting TS improved significantly. It was, therefore, found that the potential, but fringe benefits observed in compressive and flexural properties needed support from larger sample sizes or a wider microstructural study.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY

Data will be made available on request.

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