



Article

Effect of Polypropylene Fibre Dosage on Portland Cement Concrete: Early-Age Compressive Strength, Workability, and Practical Dosage Guidance

Abubakar S. Mahmoud ¹, Salwa Al Siyabi ¹, Rami Hamad ¹, Majed A. A. Aldahdooh ¹ , Ali Istanbulu ^{2,*}, Seema Shajira ¹ and Azza Humaid Al Saaidi ¹

- ¹ Department of Facilities and Construction Project Management, International College of Engineering and Management, Affiliated with the University of Lancashire, UK, Muscat 111, Oman; abubakar@icem.edu.om (A.S.M.); h21000210@icemoman.net (S.A.S.); rami@icem.edu.om (R.H.); majidaldahdooh@icem.edu.om (M.A.A.A.); seema@icem.edu.om (S.S.); azza@icem.edu.om (A.H.A.S.)
- ² Civil and Construction Engineering Department, College of Engineering, A'Sharqiyah University, Ibra 400, Oman
- * Correspondence: ali.istanbullu@asu.edu.om

Abstract

The present study was conducted to systematically investigate the effect of adding Polypropylene (PP) fibre at various dosages (0–1.0 kg/m³) on the compressive strength and workability of Blended Portland Cement concrete. All mix variables were kept constant except for fibre content (w/c = 0.45), thereby allowing the dosage effect to be isolated. Standard-sized 150 × 150 × 150 mm cubes were prepared and tested for slump (ASTM C143), fresh density and early-age compressive strength BS 1881-116:1983 at 7 days and 14 days. Slump decreased monotonically from 200 mm to 160 mm as the dosage increased and remained within the EN 206 S4 (High) workability class throughout. Fresh density was essentially unaffected. The early-age compressive strength increased continuously for both test ages, reaching 51.7 MPa at 1.0 kg/m³ at 14 days. One-way analysis of variance confirmed a statistically significant dosage effect at both ages (7-day $p < 0.001$; 14-day $p = 0.003$). Based on the strength-workability trade-off, it was found that a pragmatic recommended dosage range is 0.6–0.8 kg/m³, which gives an appreciable strength improvement with a moderate decrease in workability without the need for the addition of extra admixtures. These results offer early age mix design guidance for practitioners and engineers in a wide range of construction applications and can be used to calculate a potential circular economy impact for the mix design: a 100 m³ pour at 0.8 kg/m³ could potentially divert 80 kg of PP waste from landfill or incineration if recycled PP fibres were used instead of the virgin fibres used in the study.



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Keywords: polypropylene fibre reinforced concrete; compressive strength; concrete mix design; slump; workability; sustainable concrete; circular economy; micro-reinforcement; plastic waste valorisation

1. Introduction

Besides water, concrete is the most used manufactured material in the world and is estimated to be produced at around 30 billion tons per year globally [1,2]. Concrete, the mainstay of the built environment, is expected to continue to expand its market share, especially in regions undergoing rapid urbanisation [3]. However, its inherent brittleness,

defined by low tensile strength, sensitivity to cracking and sudden failure under overload, has inspired continued scientific research since the pioneering work of [4,5], who used fracture mechanics to investigate fibre reinforcement with closely spaced wire reinforcement, thereby initiating the modern era of fibre-reinforced concrete (FRC) research. PP is a particularly well researched synthetic fibre as it is low in density, inert to the highly alkaline cement environment, does not absorb water and can be used in its virgin form or as a post-consumer recycled [6,7]. PP accounts for about 19–20% of global plastic production, which is about 80 million tons per year, but only about 11% of it is currently recycled, making it one of the most common plastics, with enormous quantities going to landfill, incineration and the natural environment [8]. Using recovered PP in concrete thus serves two goals at once: a persistent, continuously growing waste stream is diverted from the environment, and a functionally useful micro-reinforcement agent is added to the most widely used building material in the world.

Of practical importance is the use of PP fibres to reduce plastic shrinkage cracking [5]. During casting, high temperatures, low relative humidity, and wind speed increase the evaporation of surface moisture, resulting in tensile stresses that may exceed the tensile strength of freshly placed concrete [9]. The study has shown that even small amounts of micro-synthetic fibres significantly lower the plastic shrinkage crack area due to the ability of micro-synthetic fibres to bridge incipient crack planes [10,11], and that the construction sector is ideally suited to achieve the goals of the circular economy through the use of large volumes of recovered PP waste in a functional structural sense [12,13]. Even with this double value proposition and a vast literature on the subject, there are still important knowledge gaps in the range of low additions that are most interesting from the site's point of view, between 0 and 1.0 kg/m³. Some studies have observed up to 70% improvement in early-age strength at high volume fractions [14]. While others have reported a marginal reduction in strength at high fibre volume fractions due to challenges in compaction [15], which may be attributed to sensitivity to mix design, fibre geometry, and dosage expression, and to a lack of studies in which dosage was varied strictly without other mix design factors affecting it. This paper aims to fill those gaps by systematically studying the effect of the six dosages of PP fibres (0, 0.2, 0.4, 0.6, 0.8, 1.0 kg/m³) with the combined use of a single binder system and the same mix constituents through a fully controlled experimental investigation, thereby giving mix design guidance to practitioners in different construction scenarios. The novelty of this study is the systematic incremental variation of PP fibre dosage from 0 to 1.0 kg/m³, the attention paid to the early age strengths (7 and 14 days), which are less represented in the literature, and the explicit identification of a practical strength–workability dosage range of 0.6 to 0.8 kg/m³ PP fibre without depending on additional admixtures. The contribution is deliberately practical rather than mechanistic: a controlled, single-variable dosage sweep at low, site-relevant dosages, with complete specimen-level early-age data traceable to accredited third-party laboratory records.

2. Background to Study

2.1. Polypropylene Waste: Environmental Context and Circular Economy Rationale

The global challenge in handling PP, as discussed in Section 1, and the large volume of plastic flows exacerbate the problem, as the amount of unrecovered PP waste far exceeds recycling capacity in most parts of the world, given a production volume of around 80 million tons per year [16,17]. As the world's largest consumer of raw materials by mass, the construction industry has a unique opportunity to incorporate and valorise large volumes of this recovered polymer waste at scale, making it a Structural Asset [18]. Ref. [13] also highlights that strategies for material circularity in construction help reduce the pressure to extract natural aggregates, which are scarce in many areas. Parallel low-carbon strategies

for cement-based composites, such as high-volume fly ash, microsilica, and rice husk ash systems, are being pursued across structural and geotechnical applications [19,20]. On a global scale, the volume of concrete produced is so high that even small substitution rates would divert many millions of tons of waste within the circular economy [21].

2.2. Fibre-Matrix Mechanics and the Interfacial Transition Zone

The mechanical role of PP fibres in concrete is governed by crack bridging, stress redistribution, and the alteration of the failure mode from brittle to quasi-ductile [14]. At the microstructural level, fibres that span the crack plane make it difficult for the crack to open, due to forces applied by the fibre-matrix bond, which depend on aspect ratio, surface roughness, and the quality of the interfacial transition zone (ITZ). The ITZ in PPFRC exhibits higher porosity and a lower elastic modulus, which constitute structural weaknesses that, if present at large scales, can hinder load transfer and reduce compressive strength [22]. Below 1.0 kg/m^3 , fibres act as secondary micro-reinforcement, controlling plastic shrinkage cracks and delaying the formation of microcracks during early hydration, leading to higher effective compressive strength compared to controls [10].

2.3. Evidence on the Compressive Strength

The literature shows real empirical diversity regarding the effect of PP fibres on compressive strength. Ref. [14] found a strength enhancement of up to 70% at a volume fraction of about 1.0%, which was attributed to effective crack bridging. On the other hand, Ref. [23] observed slight decreases in the compressive strength of two-stage systems due to compaction challenges associated with the fibre and the creation of additional voids. Ref. [24] investigated the effects of macro-PP fibres in UHPCs, which revealed that they had little effect on the compressive strength of the UHPCs, but significantly increased the fracture energy by a factor of 2.5, indicating that the primary benefit of these fibres is energy absorption after cracking. A review of macro plastic fibres in concrete [25] similarly reported improved post-cracking energy absorption at comparable dosages, without a significant reduction in static compressive strength. In contrast, engineered cementitious composites achieve strain-hardening and greatly enhanced ductility at much higher fibre fractions, often using hybrid PP-PVA systems [26]; the present study instead addresses low, site-relevant monofilament PP dosages in conventional structural concrete. A study on the durability of SCC incorporating 1% vol. PP fibres, conducted by [27], showed that the SCC mixture had 72% increased resistance to freeze-thaw, 54% increased resistance to sulphate attack, and 24% increased resistance to acid attack after 92 days. Finally, it should be noted that the workability loss associated with the inclusion of fibre can have indirect effects on compressive strength: if compaction is adversely affected by the loss of workability, the concrete's void content increases, and the effective cross-sectional area available for load transfer decreases. This interaction means that identical compaction effort and a constant w/c ratio for all mixes are prerequisites for isolating the fibre dosage effect, which was carefully controlled in the present study.

2.4. Workability Implications

One of the most consistent outcomes in the literature on PPFRC is a loss of workability with the addition of PP fibre. Even at low volume fractions, fibres significantly increase the specific surface area of the solid phase, allowing entrained free water to be absorbed and hindering relative movement between aggregates and paste [28]. Within the 0–1.0 kg/m^3 range, there have been reports of 10–25% reductions in workability relative to control mixes, but workability remains within operationally acceptable ranges. For higher fibre content ($>0.8 \text{ kg/m}^3$), the use of high-range water-reducing admixtures is common to improve the workability without changing the w/c ratio [10,28].

2.5. Gaps in the Literature That This Study Addresses

Three main gaps are addressed: (i) the lack of incremental, fully-controlled dosage studies within the range 0–1.0 kg/m³, for which fibre dosage is the only independent variable; (ii) the limited early age (7- and 14-day) strength data in the literature for low-dosage PPFRC, particularly relevant to construction scheduling and formwork removal decisions; and (iii) the lack of data from controlled dosage studies using consistent material systems, which helps to create uncertainty about transferability of global data in light of differing local material properties. The lack of 28-day data in the current study is recognised as a limitation, as discussed in Section 5.5, but the early-age results remain of practical value and are a necessary stepping stone for longer-term programmes.

3. Materials and Experimental Methodology

3.1. Research Methodology

The study was designed as a single-factor experiment, with the dosage of PP fibre as the only independent variable, varied across six concrete mixes, while all other components, processes, and environmental conditions were held constant. As seen in Figure 1, the overall research methodology sequence adopted was:

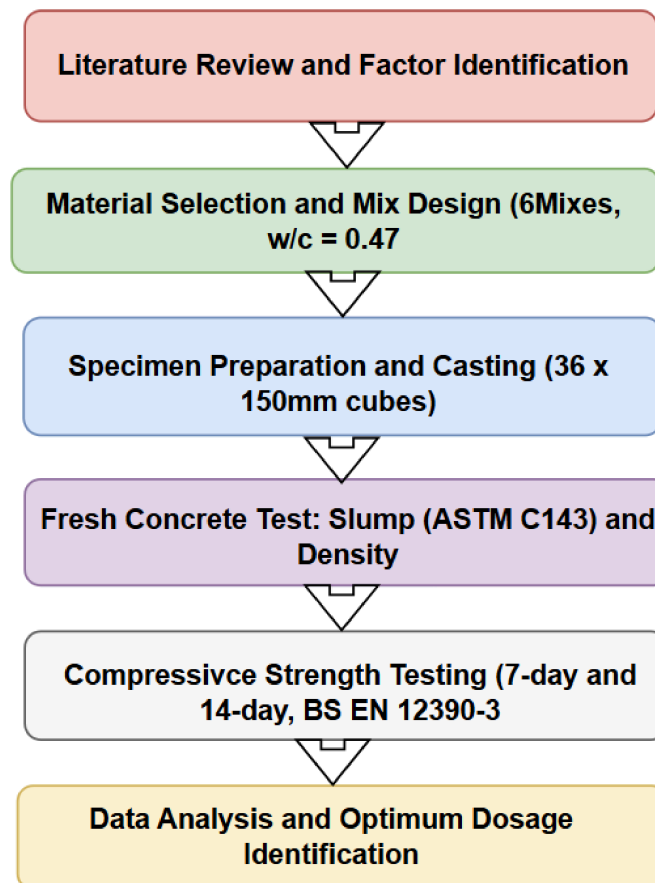


Figure 1. Research methodology flowchart: six-stage sequence from literature review to recommended dosage identification. Figure created by the authors.

3.2. Constituent Materials

All mixes used Blended Portland Cement (BPC) from Al Tasnim Cement Products LLC (Muscat, Oman), which is CE-certified (EN 197-1:2011 [29]). The fine aggregate was washed, and locally available processed sand was mixed to produce an acceptable particle size distribution. Coarse aggregate was crushed limestone with nominal sizes of 10 mm and

20 mm (from a local supplier in Muscat, Oman). For general-purpose micro-reinforcement, the most common fibre geometry is the straight monofilament with a nominal length of around 18 mm, which is also used for the PP fibres (obtained from a local supplier in Muscat, Oman). Polypropylene is also employed in concrete in other morphologies, for example as hollow spheres in polymer-composite lightweight concretes for floating structures, where it modifies both thermal and strength behaviour [30]. The main fibre characteristics were nominal fibre diameter about 18 μm , fibre density 0.91 g/cm^3 , tensile strength ≥ 300 MPa, elastic modulus around 3.5–4.5 GPa and elongation at break about 15–20% and no surface chemical treatment was used. These properties (Table 1) are in line with the general purpose PP monofilament fibres available in the market [14].

Table 1. Physical and mechanical properties of PP monofilament fibres used in this study.

Value	Property
Straight monofilament (virgin PP)	Type
18 mm	Nominal length
$\sim 18 \mu\text{m}$	Nominal diameter
0.91 g/cm^3	Density
≥ 300 MPa	Tensile strength
3.5–4.5 GPa	Elastic modulus
15–20%	Elongation at break
None (untreated)	Surface treatment
High (chemically inert in cement paste)	Alkali resistance

A mid-range water-reducing admixture (obtained from a local supplier in Muscat, Oman) was incorporated at constant proportion across all mixes. Potable water conforming to construction mixing standards was used throughout.

3.3. Mix Design

Six mixes were prepared: a control mix (M0) without fibres and five mixes (M1 to M5) fibre-reinforced with 0.2 kg/m^3 , 0.4 kg/m^3 , 0.6 kg/m^3 , 0.8 kg/m^3 , and 1.0 kg/m^3 of fibres, respectively. Another way to avoid these factors and keep the fibre content as the only independent variable was to hold all other constituent quantities (cement, water, fine aggregate, coarse aggregate) constant across the six mixes, at a constant w/c ratio of 0.45, as recorded in the laboratory batch mix-design sheets. At these very low dosages ($\leq 1.0 \text{ kg}/\text{m}^3$, approximately 0.1% by volume), the addition of fibre has a negligible effect on yield, so no compensating aggregate adjustment was required. The mix proportions are tabulated in Table 2.

Table 2. Concrete mix proportions for all six mixes (per m^3).

Mix ID	PP Fibre (kg/m^3)	Cement (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Water (kg/m^3)	w/c Ratio
M0 (Control)	0.0	400	835	1060	176	0.45
M1	0.2	400	835	1060	176	0.45
M2	0.4	400	835	1060	176	0.45
M3	0.6	400	835	1060	176	0.45

Table 2. Cont.

Mix ID	PP Fibre (kg/m ³)	Cement (kg/m ³)	Fine Agg. (kg/m ³)	Coarse Agg. (kg/m ³)	Water (kg/m ³)	w/c Ratio
M4	0.8	400	835	1060	176	0.45
M5	1.0	400	835	1060	176	0.45

Note: mix proportions correspond to the laboratory batch mix-design sheets (Al Tasnim Cement Products LLC, 2 April 2026): fine aggregate comprises washed wadi sand (725 kg/m³) plus fine sand (110 kg/m³); coarse aggregate comprises 10 mm (400 kg/m³) plus 20 mm (660 kg/m³) crushed aggregate; the water shown is the moisture-corrected total batch water at a nominal w/c of 0.45.

3.4. Preparation and Curing of Specimens

The concrete was produced in a drum mixer in a standardised, staged sequence, first the dry materials (cement, aggregates, PP fibres) were mixed for 2 min, then the admixture pre-mixed in mixing water was slowly added for 1 min, and the last 2 min were used for final wet mixing. The total mixing cycle time was 5 min (laboratory programme). This reduced the chance of fibre balling, an issue caused by insufficient dispersion that leads to fibre accumulation in certain spots, resulting in abnormally strong or weak results [14]. The casting was done in standard 150 mm cube moulds, which were oiled before casting. Concrete was cast in two layers, the first tamped with a tamping rod (25 strokes per layer) and externally vibrated. A total of 36 cubes were obtained by casting six cubes for each mix (three for 7-day testing and three for 14-day testing). The three specimens per mix-age combination is in line with the normal practice for exploratory concrete research in accordance with BS 1881-116:1983. Standard deviations (SD) and coefficients of variation (COV) were computed from the individual specimen strengths recorded in the laboratory worksheets. All COV values were less than 1.6%, which indicated good within-batch repeatability and the validity of using three-specimen means as representative of the mix-age conditions. No abnormal failure of the specimens was noted upon testing. The specimens were placed under wet hessian and polyethene sheeting, kept for 24 h at about 25 °C and demoulded and water-cured at 23 ± 2 °C until the age of the tests. The specimen preparation sequence is shown in Figure 2.

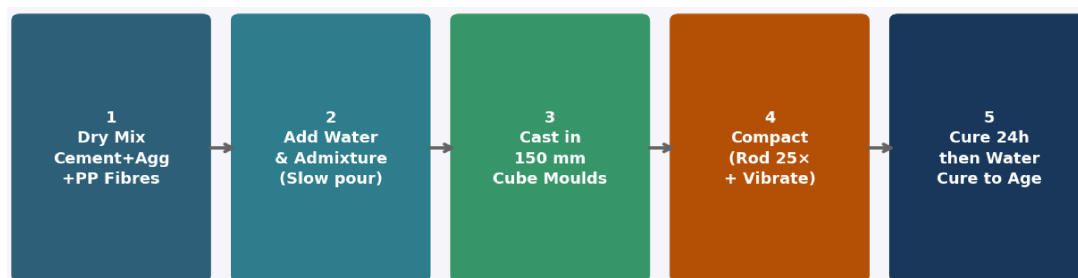


Figure 2. Specimen preparation sequence: (1) dry mixing; (2) water and admixture addition; (3) casting in 150 mm cube moulds; (4) layer-by-layer compaction; (5) water curing to test age.

One-way ANOVA across the fibre-reinforced mixes confirms that PP fibre dosage has a statistically significant effect on compressive strength at both test ages (7-day: $F(4,10) = 13.6$, $p < 0.001$; 14-day: $F(4,10) = 8.85$, $p = 0.003$). Strength increases approximately linearly with dosage (7-day slope 2.42 MPa per kg/m³, $R^2 = 0.65$; 14-day slope 3.33 MPa per kg/m³, $R^2 = 0.77$; both $p < 0.001$). Differences between adjacent dosage steps are not individually significant, so the results are interpreted as a dose-response trend with an early-age plateau beyond about 0.6 kg/m³, rather than as resolvable step-to-step differences.

3.5. Testing Procedures

3.5.1. Workability (Slump Test ASTM C143)

The workability of fresh concrete was evaluated by the standard slump cone test [31]. ASTM C143/C143M was performed right after each mix cycle. The results were grouped according to the EN 206 [32] workability classification. At the same time, the temperature of the fresh concrete was measured at mid-depth of the mix using a calibrated digital thermometer.

3.5.2. Fresh Density

Fresh density was determined by measuring the volume of a standardised sample in a rigid container of known volume with a calibrated electronic balance (precision ± 0.01 kg). The density was expressed as mass/volume (kg/m^3) and was the mean of two measurements for each mix, rounded to the nearest $1 \text{ kg}/\text{m}^3$, commensurate with the precision of the balance and container used (approximately $\pm 1 \text{ kg}/\text{m}^3$).

3.5.3. Compressive Strength BS 1881-116:1983

The compressive strength tests were carried out at 7 and 14 days using a calibrated servo-hydraulic compression testing machine at a loading rate of $0.2\text{--}0.4 \text{ N}/\text{mm}^2\cdot\text{s}$, in accordance with BS 1881: Part 116: 1983 [33]. Strength was determined as $f_c = P/A$, where P is the maximum load at failure, and A is the nominal cross-sectional area (0.0225 m^2). Reported values are the averages of three specimens at each mix-age combination.

3.6. Statistical Analysis

Differences among the fibre-reinforced mixes (M1–M5), for which complete specimen-level data are available, were assessed by one-way analysis of variance (ANOVA) at a significance level of $\alpha = 0.05$, complemented by linear regression of strength on fibre dosage. Because the fibre-free control mix could not be included in hardened-strength testing (Sections 4.2 and 5.5), the analysis is confined to the fibre-reinforced series and no fibre-versus-control strength comparison is made.

4. Results

The slump values, EN 206 workability classifications, fresh density measurements, and percentage change in slump of the mixes relative to the control are given in Table 3. The trend of slump vs. dosage is shown graphically in Figure 3 and the fresh densities in Figure 4.

Table 3. Fresh concrete properties: slump, workability class, fresh density, and change vs. control.

Slump Change vs. Control	Fresh Density (kg/m^3)	Slump Class (EN 206)	Slump (mm)	PP Fibre (kg/m^3)	Mix ID
Control	2470	S4 (High)	200	0	M0 (Control)
−2.50%	2470	S4 (High)	195	0.2	M1
−5.00%	2472	S4 (High)	190	0.4	M2
−10.00%	2471	S4 (High)	180	0.6	M3
−15.00%	2473	S4 (High)	170	0.8	M4
−20.00%	2480	S4 (High)	160	1	M5

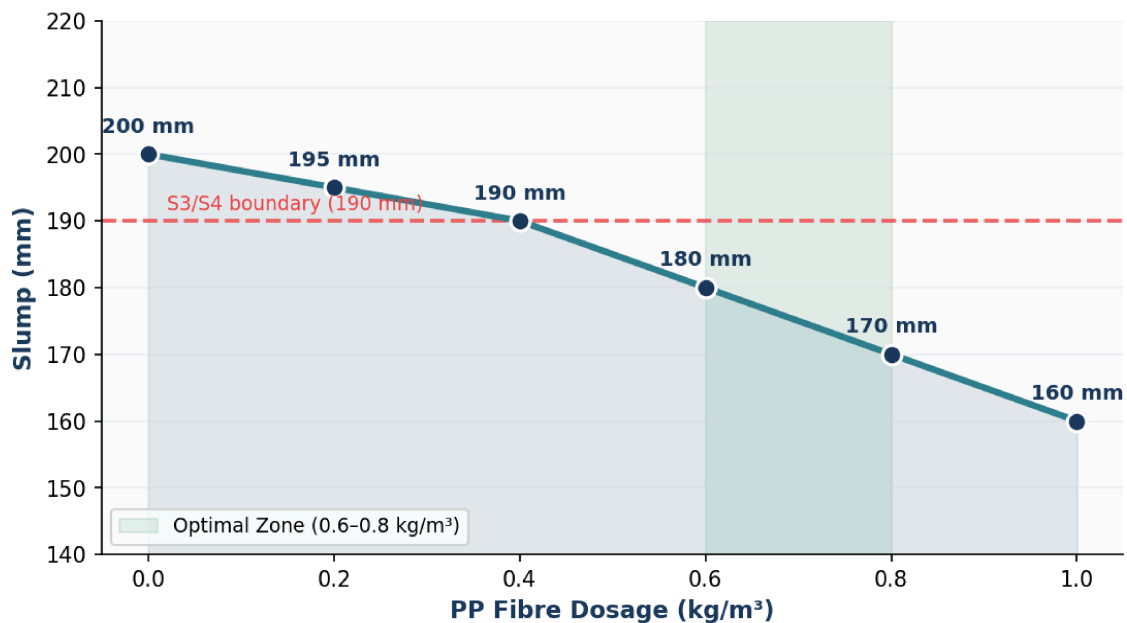


Figure 3. Slump value versus PP fibre dosage (0–1.0 kg/m³). Dashed red line marks the EN 206 lower boundary of S4 at 160 mm (S4 = 160–210 mm). The green-shaded zone indicates the recommended 0.6–0.8 kg/m³ dosage range. All mixes remained within the S4 workability classification.

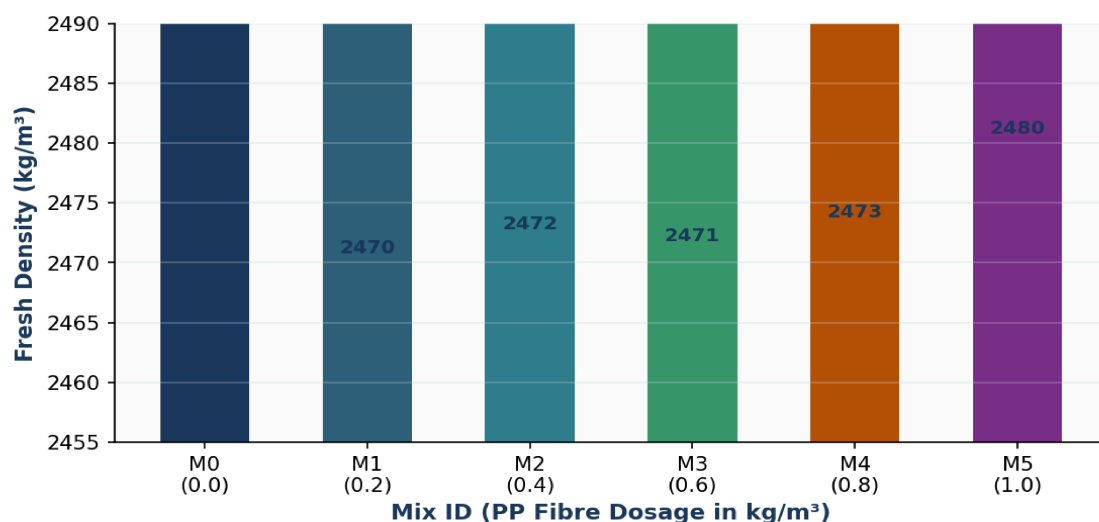


Figure 4. Fresh concrete density for each mix (M0–M5). Values remain essentially constant (2470–2480 kg/m³), confirming negligible volumetric impact of PP fibres at these dosages. The recorded fresh density for M5 was 2477 kg/m³ (reported to the nearest 10 kg/m³ as ≈2480 kg/m³), approximately 0.3% above the 2470 kg/m³ recorded for the other mixes; this small, single-batch difference lies within normal batching and rounding variation and is not interpreted as a fibre effect.

A monotonic decrease in slump is clearly visible. Slump was measured as a single value for each batch, as is usual in mix development studies; the between-batch variation is not measured in this study. The control mix (M0) achieved 200 mm firmly within EN 206 class S4 (High, defined as 160–210 mm). Mixes M1–M3 (0.2–0.6 kg/m³) retained S4 classification at 195–180 mm. At 0.8 kg/m³ (M4), the slump dropped to 170 mm, and M5 (1.0 kg/m³) recorded 160 mm, representing a 20% total reduction, consistent with reported ranges for comparable dosages [25,34]. Despite this progressive reduction, all mixes were found to be essentially placeable by standard site methods without supplementary admixtures, the S4 (High) range being suitable for slabs, columns, and foundations placed by skip or pump under a wide range of site conditions.

The fresh density was effectively constant at 2470–2480 kg/m³ across the full dosage range and did not materially affect unit weight at any of the PP fibre quantities. From first principles, this is what one would expect, since at 1.0 kg/m³, the PP fibres take up about 1.1 L/m³ of the concrete (volume fraction 0.11%). Because the bulk density of the aggregate and paste being displaced to make room for this volume is about the same as the bulk density of the mix, there will be no measurable unit weight change—and indeed none was measured. The small increase (1.0 kg/m³: 2480 vs. 2470 kg/m³) is not considered a systematic trend unless repeated measurements are done but falls within the measurement uncertainty.

4.1. Compressive Strength Development

The 7-day and 14-day compressive strengths for all six mixes are shown in Table 4, along with the percentage variations relative to the lowest fibre dosage (0.2 kg/m³, M1). Both strength development curves are shown in Figure 5. The individual specimen strengths, together with the corresponding SD and COV for each mix, are reported in Table 5.

Table 4. Compressive strength results at 7 and 14 days of water curing (mean of 3 specimens per mix-age).

14-Day vs. 0.2 kg/m ³ (M1)	7-Day vs. 0.2 kg/m ³ (M1)	14-Day fc (MPa) [avg.]	7-Day fc (MPa) [avg.]	PP Fibre (kg/m ³)	Mix ID
— (ref)	— (ref)	49.0	45.5	0.2	M1
1.00%	2.20%	49.5	46.5	0.4	M2
2.00%	4.40%	50.0	47.5	0.6	M3
3.70%	4.00%	50.8	47.3	0.8	M4
5.50%	4.40%	51.7	47.5	1.0	M5

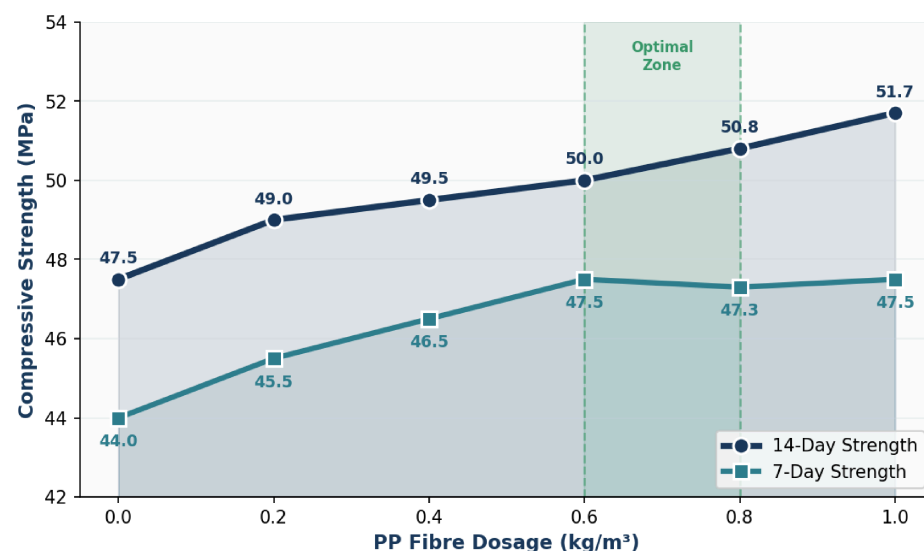


Figure 5. Compressive strength development at 7-day (teal) and 14-day (navy) curing ages versus PP fibre dosage. Both series show a progressive increase in strength. The widening gap between 7-day and 14-day results at higher dosages indicates that the fibre-matrix bond quality is maturing as hydration continues. Green dashed lines indicate the recommended dosage window (0.6–0.8 kg/m³).

Table 5. Individual specimen compressive strengths, standard deviations (SD), and coefficients of variation (COV) for all mix-age combinations (M1–M5).

COV (%)	SD (MPa)	Mean (MPa)	Spec 3 (MPa)	Spec 2 (MPa)	Spec 1 (MPa)	PP Fibre (kg/m ³)	Mix ID
7-Day Results (tested 9 April 2026; cast 2 April 2026)							
1.1	0.5	45.5	45.5	45	46	0.2	M1
1.1	0.5	46.5	46	46.5	47	0.4	M2
0	0	47.5	47.5	47.5	47.5	0.6	M3
0.6	0.29	47.3	47.5	47	47.5	0.8	M4
1.1	0.5	47.5	48	47	47.5	1	M5
14-Day Results (tested 16 April 2026; cast 2 April 2026)							
1	0.5	49	49	49.5	48.5	0.2	M1
1	0.5	49.5	49	49.5	50	0.4	M2
1	0.5	50	49.5	50.5	50	0.6	M3
1.5	0.76	50.8	51.5	50	51	0.8	M4
1.5	0.76	51.7	51	52.5	51.5	1	M5

Individual specimen strengths for the fibre-reinforced mixes (M1–M5) were obtained from Al Tasnim Gulf LLC laboratory worksheets dated 9 April 2026 (7-day) and 16 April 2026 (14-day). The fibre-free control mix (M0) was not included in the hardened-strength testing programme; its cubes and the associated records were subsequently lost in a laboratory flooding incident, so no control compressive strengths are reported, and the hardened-strength analysis is confined to the fibre-reinforced series. The control mix contributes only fresh-state properties (slump and density), as reported in Table 3.

All fibre-reinforced mixes (M1–M5) exhibited coefficients of variation below 1.6%, indicating excellent repeatability and suggesting that the observed strength differences exceed normal laboratory testing scatter for concrete of comparable strength class.

At 7 days, compressive strength increased with fibre dosage from 45.5 MPa at 0.2 kg/m³ (M1) to 46.5 MPa at 0.4 kg/m³ (M2), with M3 (0.6 kg/m³), M4 (0.8 kg/m³) and M5 (1.0 kg/m³) clustering closely at 47.3–47.5 MPa. The near-plateau between 0.6 and 1.0 kg/m³ at 7 days suggests that the main strength-enhancing mechanisms (plastic shrinkage and early-age microcrack control) are saturated in this dosage range.

At 14 days, the dose–response is more distinct and systematic, strength increasing steadily with dosage: 49.0 MPa at 0.2 kg/m³ (M1), 49.5 MPa (M2), 50.0 MPa (M3), 50.8 MPa (M4) and 51.7 MPa at 1.0 kg/m³ (M5). The growing separation between low and high dosages over time is mechanistically consistent with PP fibres becoming more effective as the cement hydration network develops, which is associated with an increase of ITZ cohesion and stress transfer efficiency, as reported for similar cementitious systems over time [24].

4.2. Strength-Workability Trade-Off Analysis

Figure 6 shows the strength-workability trade-off diagram, the main engineering contribution of this study, with the recommended dosage zone indicated.

At 0.6 kg/m³ (M3), the 14-day strength of 50.0 MPa is obtained with a slump of 180 mm, only a 10% reduction from the fibre-free reference slump of 200 mm. The step from M3 to M5 (1.0 kg/m³) provides an additional 3.4% of 14-day strength, but at the cost of an extra 11% reduction in workability, a significantly less attractive ratio. This reduction beyond 0.6 kg/m³ supports identifying 0.6–0.8 kg/m³ as the practical recommended range for general construction, where on-site workability retention may already be limited by hot, dry conditions. It should be emphasised that this range reflects a transparent engineering

judgement rather than a unique mathematical optimum: in a simple two-objective desirability analysis of the present data, equal weighting of strength and workability favours approximately 0.4 kg/m^3 , whereas weighting early-age strength more heavily favours $0.6\text{--}0.8 \text{ kg/m}^3$. The recommended range is therefore conditional on prioritising early-age strength while remaining within the S4 workability class.

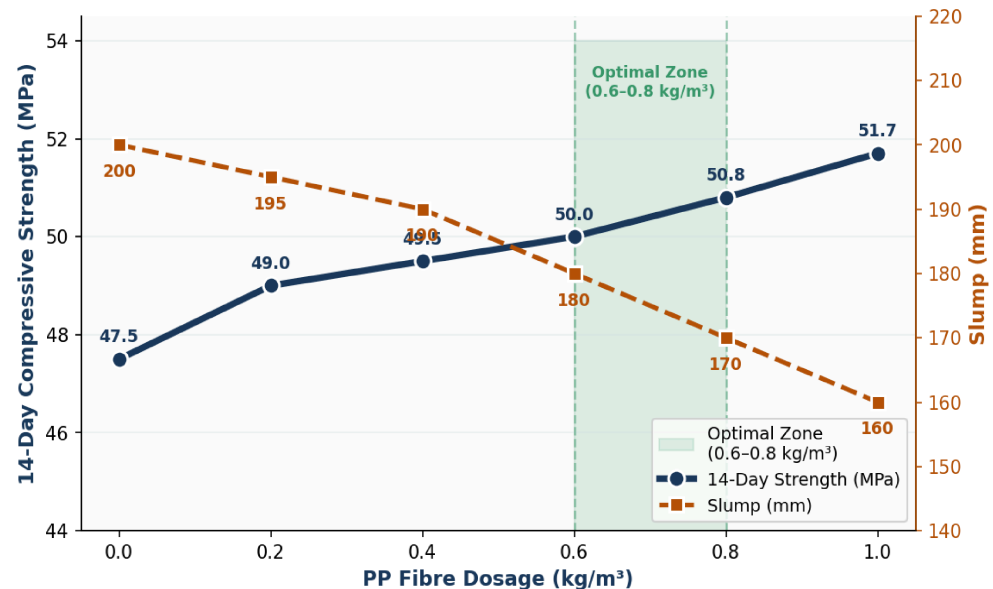


Figure 6. Strength-workability trade-off diagram: 14-day compressive strength (navy line, left axis) versus slump (orange dashed line, right axis) across the PP fibre dosage range. The green-shaded zone ($0.6\text{--}0.8 \text{ kg/m}^3$) represents the recommended practical dosage range, where meaningful 14-day compressive strengths (about 50–51 MPa) are achieved with a workability reduction of only 10–15%, while still permitting effective compaction without supplementary admixtures.

5. Discussion

5.1. Mechanistic Interpretation of the Development of Strength

The compressive strength results showed a systematic dose–response increase across the fibre series at 14 days, which is consistent with, but at the lower end of, the literature for PPFRC. This is due to the narrow range of dosages studied (max $\sim 0.1\%$ by volume), the strong matrix used (a dense, low-porosity matrix, with 14-day fibre-mix strengths of about 49–52 MPa), and the use of straight, smooth monofilament fibres rather than fibrillated or surface-treated fibres. Strength enhancement is consistent with two overlapping mechanisms reported in the literature: (i) PP fibres inhibit the plastic shrinkage crack formation during early hours after casting, maximising effective cross sectional area for load transfer [6,35] (ii) During hardening, the fibres arrest propagation of microcracks under compressive loading by bridging incipient crack faces and making load transfer more difficult, requiring more energy for microcrack coalescence and postponing unstable fracture. The gradual increase in fibre contribution from 7 to 14 days indicates that as hydration products continue to fill the ITZ, fibre-matrix bonding strengthens, leading to increased load sharing and load-transfer efficiency [24]. The nearly flat trend in 7-day gains of $0.6\text{--}1.0 \text{ kg/m}^3$ is informative from a mechanistic perspective. In this study, the 7-day strength of 47.5 MPa at 0.6 kg/m^3 of fibre rose to 47.5 MPa at 1.0 kg/m^3 of fibre—an incremental gain of effectively zero, with a 67% increase in the amount of fibre. This saturation is due to two counteracting mechanisms: the addition of further fibres yields a proportionately lower number of unbridged crack planes (diminishing crack-bridging returns) and, at the same time, increases the porosity in the ITZ per unit volume of concrete, leading to marginal compaction losses, even when standardised vibration is applied. Conversely, the

14-day test results indicate that the separation between M4 (0.8 kg/m³, 50.8 MPa) and M5 (1.0 kg/m³, 51.7 MPa) remains constant, suggesting that the maturing hydration network steadily counteracts the initial weakness of the ITZ as the C-S-H products deplete the fibre-matrix interface [14,22].

5.2. Workability: Rheological Mechanisms and Construction Implications

The observed slump reduction is consistent with established principles of the rheology of fibre-reinforced cement systems. PP fibres bring a huge number of individual fibres even at 1.0 kg/m³ (approx. 0.1% by volume). 1.0 kg/m³ corresponds to in the order of 200 million individual fibres per cubic meter of concrete, which will create a film of paste on the hydrophobic surface of each fibre and lubricate movement between fibres and aggregate particles, all of which will reduce the free paste available to lubricate the bulk mix [34], at 18 mm length and ~18 µm diameter. This accounts for the observed almost linear slump reduction: for every 0.2 kg/m³ increase, slump dropped by around 8–10 mm, a linear and predictable relationship that would aid on-site workability planning based on dosage. Importantly, the absolute slump range maintained in the programme (160 to 200 mm) covers the entire range of operationally useful slumps for fresh concrete, as normally used in most commercial and residential buildings under most site conditions. The lowest recorded slump was 160 mm at 1.0 kg/m³, which is acceptable for vibrated concrete placements and within the EN 206 S4 (High) limits. This is common practice and does not impose a significant cost burden when using high-range water reducers at dosages greater than 0.6 kg/m³. To put this in perspective from an economic point of view, at 0.8 kg/m³, this additional PP fibre material cost is estimated to be approximately USD 0.50 to USD 0.80 per m³ of concrete (assuming indicative market prices of approximately USD 0.50 to USD 0.80 per kg of virgin PP monofilament fibres; recycled PP will be generally lower) which is modest relative to the typical in-situ concrete cost of USD 80 to USD 120/m³ [36] and may be partially offset by cost savings due to reduced plastic shrinkage cracking remediation and repair frequency at the site.

5.3. Contextualisation Within Global Literature

Table 6 compares the results of this study with recent high-impact publications on PP fibre-reinforced concrete, highlighting both the agreement with the current published work and the original contribution this study has made through the controlled incremental design of a series of concrete products, with a consistent material suite. To give an idea of the volume fraction, 1.0 kg/m³ of PP fibre (with a density of ~0.91 g/cm³) corresponds to a volume fraction of ~0.11%; the volume-fraction notation used in some cited studies can be converted using this relationship for cross-study comparison.

The single-factor controlled-dosage design of the present study is unique in that it investigates the dosage range most practical for engineering. Although the strength improvements are smaller than those reported by [14], they are like those reported by [15] and fall within the practical range identified by [11] for mixes with similar baseline strength. A surprising finding with relevance for practitioners is that there was no loss of strength at any tested dosage, attributed to the careful mixing protocol that avoided fibre balling and to the constant w/c across all mixes.

Table 6. Comparison of key findings with recent literature on PP fibre-reinforced concrete.

Key Observation	Workability Effect	fc Change	Dosage	Reference
Optimal ~1.0%; significant crack-bridging	Slump reduction	Up to +70%	0.5–1.5% vol.	Malek et al. [14]
Improved abrasion/tensile; marginal fc reduction	Slump reduction	Slight reduction	Varies	Alyousef et al. [15]
Fracture energy $\times 2.5$; ductile failure mode	N/A	Negligible	Macro-PP in UHPC	Birol & Avcialp [24]
Lightweight + sustainable; PP bridges pores	Maintained	Stability improved	PP geopolymer foam	Ahiskalı et al. [11]
72% resistance vs. freeze-thaw at 92 days	Acceptable	Best durability	1% vol.	Chen et al. [27]
Recommended 0.6–0.8 kg/m ³ ; strength-workability balance without admixtures	20% reduction at 1.0 kg/m ³	49.0–51.7 MPa at 14 days (dose–response)	0.2–1.0 kg/m ³	Present study (2026)

5.4. Sustainable Construction Implications and Circular Economy Context

The use of PP fibres in concrete is directly linked to global sustainability and the overall programme to integrate the circular economy into the construction sector. The use of recovered post-consumer PP in concrete enables construction projects to address plastic waste management challenges while enhancing the durability and sustainability of concrete infrastructure, thereby reducing its lifecycle embodied carbon through longer product lifespans and fewer repairs [13,27]. The results have confirmed the suitability of PPFRC at 0.6–0.8 kg/m³ for industrial floor slabs, pavements, precast elements, and repair mortars across a wide range of climatic and geographic conditions. As an illustrative modelled scenario of the potential circular economy benefit, the mix design employed in this case (0.8 kg/m³ PP fibre) was verified using virgin monofilament fibres. If, however, equivalent recovered post-consumer PP fibres with the same geometry were substituted (as identified in Section 5.5 as a priority for further investigation), it is possible that a single pour (100 m³) could divert around 80 kg of PP waste from landfill or incineration. If scaled to a fraction of the concrete production worldwide, such substitution would lead to a multi-million ton diversion of polymer waste from environmental pathways, providing an attractive motivation for future work for validation purposes. It is especially effective in resisting plastic shrinkage cracks under harsh environmental conditions, such as high ambient temperatures, low relative humidity, or high solar radiation, which increase evaporation rates in fresh concrete.

5.5. Limitations and Future Research Directions

The following is a list of key limitations in order of priority. Compressive strength was measured only at 7 and 14 days. This 28-day value was not measured and is a major limitation: The values presented here should be taken as indicative only and are not suitable for design acceptance of structures or for comparison with most published research work for PPFRC. However, low variability has been observed only in the fibre-reinforced mixes, and the dosage–response trends are systematic, giving confidence that the reported behaviour at early age is representative of the investigated material system. Second, no microstructural characterisation by SEM or MIP was performed, which would

have provided direct evidence of the quality of ITZ bonding and the morphology of crack bridging. Third, no durability testing (water absorption, RCPT, drying shrinkage) was conducted, and only fresh and early-age hardened properties were therefore reflected. Fourth, the fibre-free control mix could not be included in the hardened-strength analysis: its cubes and the associated test records were subsequently lost in a laboratory flooding incident before individual control strengths were archived, so the control contributes fresh-state properties (slump and density) only and the compressive-strength results are reported as a dose–response across the fibre-reinforced series (M1–M5). Fifth, the findings are specific to the materials investigated—a blended Portland cement at w/c 0.45, local crushed aggregates, and monofilament PP fibres of the stated geometry, dosed by mass, and extrapolation to other fibre lengths, diameters, or aspect ratios, cement types, w/c ratios, or aggregate sources requires further verification. Future research needs are prioritised as: (1) to extend the compressive strength testing up to 28, 56, and 90 days and validate the trend demonstrated at early ages with standard acceptance criteria; (2) to include direct incorporation of recovered post-consumer PP fibres as a direct replacement in the fibre system, to validate the circular economy case with performance data; and (3) to examine hybrid fibre systems where PP fibres are combined with steel or basalt, since it has been found that hybridisation can simultaneously enhance the strength, tensile performance and durability compared to the results of either of the two systems alone [37].

6. Practical Recommendations

It is recommended that practitioners, mix designers and specification writers do the following based on the experimental results and the literature:

- Use 0.6–0.8 kg/m³ as the main working dosage for the ordinary structural and semi-structural concrete. Within this range, the fibre-reinforced specimens reached 14-day strengths of about 50–51 MPa, with only a 10–15% loss of workability, without additional admixtures, while still maintaining an S4 classification.
- State 1.0 kg/m³ with a high-range water-reducing admixture (ASTM C494 [38] Type F or G) for slump restoration where maximum compressive strength is required without w/c ratio change. This corresponds to the highest 14-day strength recorded in the programme, 51.7 MPa at 1.0 kg/m³.
- Always use PP fibres as part of a controlled, staged mixing protocol. The suggested sequence for site practice is: (1) dry-blend cement, aggregates, and fibres for 2 min; (2) the approximately 50% of the mixing water should be added and mixing should be done for 1 min; (3) the admixture should be added to the remaining water and mixing should be done for 2 min; (4) final mixing for 2 min. Total: ~7 min (Note: the laboratory programme was based on a 5-min cycle under controlled conditions; the longer site protocol is recommended to disperse the fibre under variable field conditions). This is a staged approach that provides a uniform fibre dispersion and avoids balling without the need for any specialist equipment.
- PPFRC (0.6–1.0 kg/m³) is recommended for: industrial floor slabs and pavements, precast concrete elements at risk of plastic shrinkage, repair and overlay mortars and for use in hot, dry, windy ambient conditions.
- PP fibres may not be used to reduce the amount of primary tensile reinforcement (steel bar or mesh) in structural elements that are designed to resist bending or shear. They are used as secondary micro-reinforcement for crack control, shrinkage mitigation, and early-age performance enhancement.
- Future specifications for sustainable concrete should consider using recovered post-consumer PP fibres instead of the virgin fibres used and validated in this study, provided there is a direct comparison of their performance. The recommended mix

design identified in this study ($0.6\text{--}0.8\text{ kg/m}^3$) can be used directly as a starting point for such a substitution trial.

7. Conclusions

This paper reported a systematic, fully controlled experimental study on the effects of PP fibre dosages ($0\text{--}1.0\text{ kg/m}^3$ in 0.2 kg/m^3 intervals) on the compressive strength and workability of BPC concrete using local aggregates. Six mix designs were investigated using slump test, fresh density test and compressive strength test at the ages of 7 days and 14 days, with maintaining all the other mix variables (w/c ratio) as constant (0.45). Six original figures have been included, comprising a research methodology flowchart, a specimen preparation diagram, a slump-dosage line chart, a fresh density bar chart, a dual-series strength development chart and a strength-workability trade-off diagram, which show the entire experimental programme and the results.

The key findings are: (i) There is progressive monotonic reduction in slump from 200 mm to 160 mm without compromising the operational S4 workability throughout; (ii) An effectively constant fresh density of $2470\text{--}2480\text{ kg/m}^3$, which confirms that PP fibres do not alter the unit weight at these dosages; and (iii) Consistent progressive increase in early age compressive strength at both 7 and 14 days, with the highest early-age strengths recorded at 1.0 kg/m^3 (47.5 MPa at 7 days and 51.7 MPa at 14 days, noting that 28-day data were not obtained and remain a priority for future validation). The increase in strength differences over time indicates improving fibre-matrix bond quality with further hydration. The analysis of the strength-workability trade-off shows that the dosage window of $0.6\text{--}0.8\text{ kg/m}^3$ is the recommended range for practical use, with significant strength gains and minimal workability losses (without additional admixtures).

These findings validate PP fibre as a sustainable, performance-enhancing material for Portland cement concrete and therefore support the use of recovered post-consumer polypropylene waste in concrete in the context of the global quest to integrate the construction sector into a circular economy. Few published studies have investigated a single factor in a controlled dosage study in the range $0\text{--}1.0\text{ kg/m}^3$ at 0.2 kg/m^3 intervals, while other mix factors were kept constant for a single binder system, as described by the authors. The study thus offers ready-to-use guidance for engineers, contractors and sustainability practitioners on an early-age mix design for a wide variety of construction situations.

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