

Polypropylene Fibers in Cementitious Composites: A Critical Review of Polymer Structure, Processing, Interfacial Behavior, and Performance

Prasad Sonar^{1,*}, Sudhir Patil²

Abstract

Polypropylene (PP) fibers are widely used as secondary reinforcement in cementitious composites, yet their performance is governed as much by polymer structure and interfacial chemistry as by dosage. This review synthesizes 55 primary sources (2003–2025, concentrated post-2015) to examine how PP molecular structure, fiber-manufacturing history, morphology, surface properties and environmental ageing govern fiber–matrix interaction and multiscale composite performance. Isotacticity, molecular weight, crystallinity and drawing ratio are shown to set the fiber's intrinsic tensile and modulus ceiling before it ever contacts cement paste. Because untreated PP presents a nonpolar surface (contact angle approximately 95–105 degrees, surface energy near 30 mN/m), wetting by the polar cement paste is poor, and the interfacial transition zone relies on friction and mechanical interlock rather than chemical bonding. Surface modification methods, including plasma and corona treatment, silane coupling, maleic-anhydride grafting and mineral coatings, are evaluated for their effect on contact angle, pull-out resistance and durability of the treatment under alkaline exposure. A consistent dosage confound is identified: reported optima cluster near 0.5–1.0% by fiber volume fraction, but many primary studies report weight-based dosage without specifying the denominator, so values are not directly comparable across the dataset. Fiber volume fraction and kg/m³ are adopted as the primary reporting units throughout. Thermal, oxidative, alkaline, freeze-thaw and UV ageing mechanisms are distinguished from ageing of the fiber–matrix interface and of the composite. Structural applications in pavements, precast elements, tunnel linings and impact-resistant elements are retained as evidence of structure–property translation rather than as the primary contribution. Sustainability is assessed quantitatively against steel, glass, basalt and natural fibers, without assuming PP is inherently sustainable. Priority research needs are standardized dosage reporting, quantitative surface-treatment durability data, and design guidance connecting polymer-level variables to composite performance.

Keywords: Polypropylene fiber, cementitious composite, polymer–matrix interface, surface modification, structure–property relationship, fiber pull-out

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INTRODUCTION

Fiber-reinforced concrete (FRC) emerged as a major branch of construction materials engineering during the latter half of the twentieth century, driven by the fundamental limitation of plain concrete: its inherent brittleness and negligible post-cracking tensile resistance. The incorporation of discrete fibers into the cement matrix transforms this brittle material into a pseudo-ductile composite capable of sustaining loads well beyond the matrix cracking point. While steel fibers were the original workhorse of FRC technology, synthetic polymeric fibers, particularly those derived from polypropylene,

have gained substantial prominence since the 1980s owing to their chemical inertness, low density, resistance to corrosion and competitive cost profile [1, 2].

Polypropylene itself is a semi-crystalline thermoplastic polymer synthesized by propene monomers. Commercially produced since 1954 following its discovery at Phillips Petroleum by Paul Hogan and Robert Banks, PP underwent rapid material evolution after Karl Ziegler and Giulio Natta's development of stereospecific Ziegler-Natta catalysts, which enabled production of isotactic PP with superior mechanical properties. By the early 1980s, melt-spinning and film-extrusion processes had been refined to yield high-tenacity fibers suitable for concrete reinforcement, and the material found its first systematic civil-engineering applications in pavement overlays and industrial flooring. The most recent decade has seen PP fibers incorporated into advanced applications including metro tunnel linings, 3D-printed concrete elements and ultra-high-performance composites [3, 4].

From a polymer-science standpoint, PP is not a uniform reinforcement material. Its performance in a cementitious matrix is set by a chain of structure-processing-property relationships that begin at the molecular level, well before the fiber is ever mixed into a concrete batch: polymer tacticity and molecular weight determine the achievable crystallinity and drawing ratio during fiber spinning; drawing ratio and crystallinity set the fiber's tensile strength and modulus; and the fiber's resulting surface chemistry, which remains nonpolar and hydrophobic regardless of how the bulk polymer was processed, controls its ability to wet and bond with the polar, alkaline cement paste (Figure 1). A review positioned in a polymer and composites journal must, therefore, treat polymer chemistry, fiber manufacturing history, and fiber-matrix interface as central subject matter, not as background context for a concrete-performance discussion.

Despite the extensive and growing body of literature on PP fiber-reinforced concrete, several unresolved questions persist from this polymer-composite perspective. The relationship between fiber morphology, surface condition and interfacial bond performance in the cement matrix remains incompletely characterized, and the quantitative evidence for specific surface-modification strategies is scattered across the polymer-composites and construction-materials literature without systematic synthesis. The behavior of PP fibers under sustained environmental exposure, including alkaline degradation, thermal cycling and UV-induced chain scission, demands more systematic investigation than has been conducted to date, and is frequently conflated in the literature with degradation of the composite rather than of the fiber or the interface specifically.

Furthermore, standardized design guidance for PP fiber dosage remains absent from most international concrete design codes, in part because studies report dosage using inconsistent and sometimes ambiguous units. This review addresses these gaps by providing a mechanistically grounded, quantitatively anchored synthesis that places polymer structure, surface chemistry and the fiber-matrix interface at the centre of the analysis, while retaining composite-performance and application evidence as the downstream validation of that structure-property chain.

REVIEW OBJECTIVE

The scope of the present review encompasses (i) the molecular structure and physical chemistry of polypropylene and its translation into fiber morphology through processing; (ii) the surface chemistry of the PP-cement interface and the methods available to modify it; (iii) dispersion, fresh-state rheology and dosage-dependent effects on mechanical performance; (iv) thermal, chemical and environmental ageing of the fiber, the interface and the composite; (v) recycled PP fibers and life-cycle considerations; (vi) structural applications, retained as evidence of structure-property translation; and (vii) a critical assessment of outstanding research gaps. A total of 55 primary research papers and standards documents have been included following the systematic screening process described in Section 2.

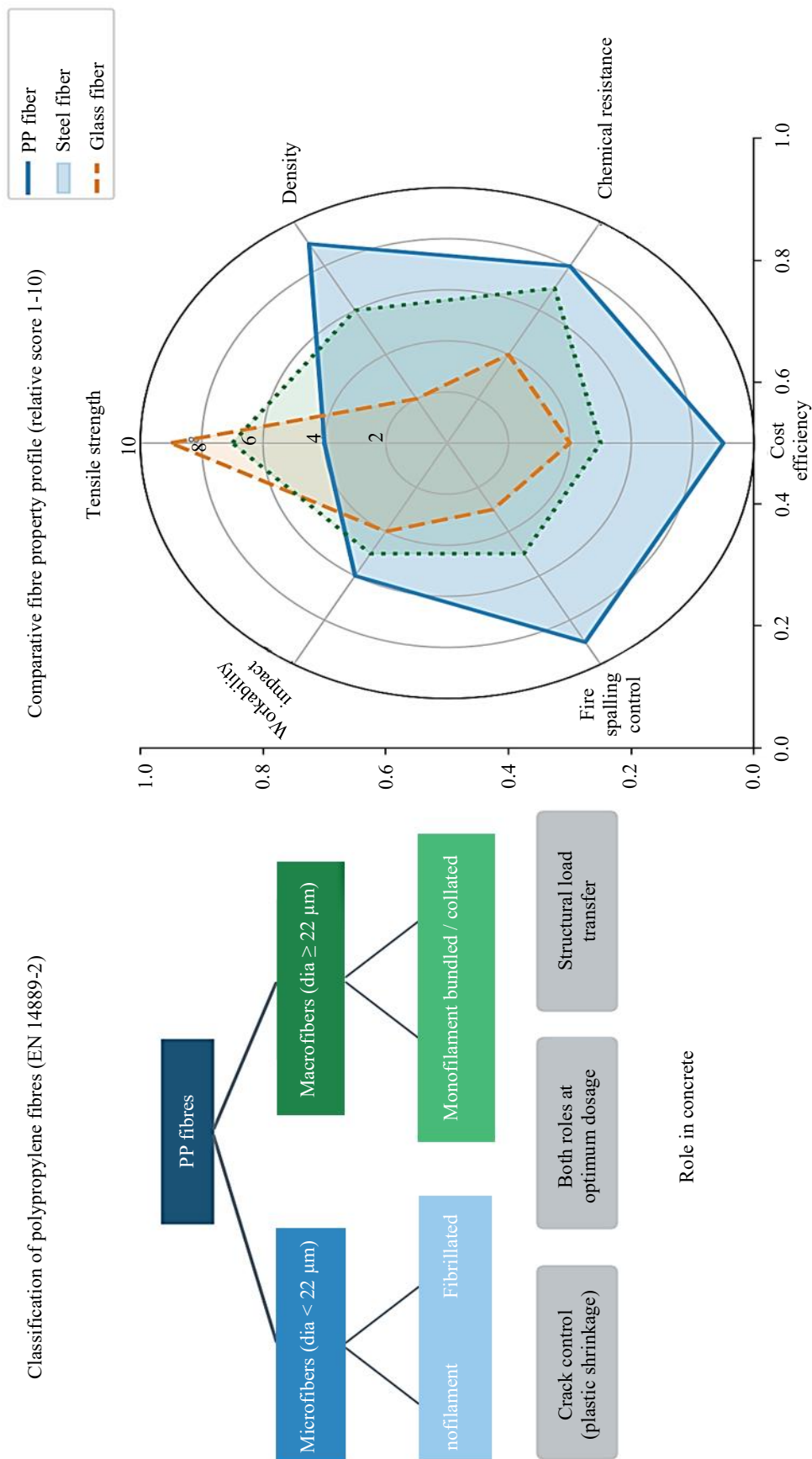


Figure 1. Classification of polypropylene fibers (EN 14889-2) and comparative fiber property profile.

REVIEW METHODOLOGY

A literature search was carried out across three databases: Google Scholar, Web of Science and Scopus, with the final search executed in July 2026. The search string combined polymer-and-interface-oriented terms with the established concrete-performance terms used in the original screening: “polypropylene fiber reinforced concrete”; “mechanical properties of polypropylene fiber concrete”; “crack control of synthetic fiber concrete”; “polypropylene fiber dosage and shrinkage”; “polypropylene fiber reinforced concrete durability and applications”; “polypropylene fiber crystallinity”; “polypropylene fiber drawing ratio”; “polypropylene cement interface”; “surface-modified polypropylene fiber concrete”; “polypropylene fiber contact angle”; “polypropylene fiber pull-out”; “interfacial shear strength polypropylene cement”; “plasma-treated polypropylene fiber”; “oxidation ageing polypropylene fiber”; and “recycled polypropylene fiber cement composite”. Literature from 2003 through 2025 was included, with most of the research analyzed drawn from 2015 onward to focus on current fiber types and testing procedures. Supplemental searching was conducted through the ASCE Journal of Materials in Civil Engineering, Cement and Concrete Composites, Construction and Building Materials, and the Journal of Applied Polymer Science.

The search began with approximately 310 records. Following de-duplication, 148 were retained for full-text screening against the following inclusion criteria: (i) polypropylene or hybrid synthetic-fiber reinforced concrete or a directly comparable cementitious composite; (ii) a peer-reviewed source reporting quantitative mechanical, interfacial or durability data; (iii) English language. During full-text review, 93 records were excluded because they reported insufficient raw data, could not separate the effect of polypropylene fiber from other simultaneously varied mix parameters, or duplicated results already captured from an earlier or more complete publication, leaving 55 records in the final dataset that serve as the basis for this synthesis.

Where a source reported fiber dosage on a mass basis, the denominator (cement mass, binder mass or total composite mass) was recorded and mass-based values were converted to volume fraction only where fiber and matrix densities were reported or could be reasonably estimated from the stated fiber type; mass-based figures without a stated conversion basis are reported as such rather than pooled with volume-fraction data. Studies were additionally classified as primarily polymer-science, interface-science or concrete-performance in orientation to track the balance of evidence across the structure-processing-interface-performance chain. Contradictory findings between studies (for example, differing optimum dosage ranges) are discussed explicitly in the relevant section rather than average without comment.

Molecular Structure and Physical Chemistry of Polypropylene

Polypropylene used in fiber manufacture is almost exclusively isotactic PP (iPP), in which the methyl side groups are arranged on the same side of the extended polymer backbone; this stereoregularity permits the tight helical chain packing responsible for PP’s relatively high crystallinity and melting point compared with atactic or syndiotactic forms, which are amorphous or only weakly crystalline and are not used in reinforcement fiber. Isotacticity, together with molecular weight and molecular-weight distribution (MWD), sets the ceiling on achievable fiber mechanical properties.

Ultrahigh-molecular-weight isotactic PP (up to approximately 1400 kg/mol) has been shown to yield melt-spun and melt-drawn fibers with tensile strength up to approximately 400 MPa, compared with approximately 50 MPa for fibers spun from commercially typical iPP of around 330 kg/mol under otherwise comparable processing, although the very high melt viscosity of ultrahigh-molecular-weight grades narrows the processing window before extrusion rupture occurs [5]. Commercial construction-grade PP fibers are produced from far lower molecular weights than this ultrahigh-molecular-weight benchmark, which is one reason their tensile strength (Table 1) sits well below the upper bound demonstrated for tailored resins.

Table 1. Polymer and fiber characteristics of principal PP fiber categories.

Property	Monofilament (Standard)	Fibrillated	Multifilament	Macro-Structural
PP content (%)	100	100	100	≥90
Manufacturing route	Melt spinning + drawing	Film extrusion + mechanical splitting	Melt spinning, multifilament bundling	Melt spinning + drawing, coarse profile
Cross-section	Round / quadrangular	Flat ribbon	Round	Round / twisted
Density (g/cm ³)	0.90–0.91	0.90–0.91	0.91	0.91–1.00
Diameter (μm)	12–36	20–40	6–18	400–900
Crystallinity (as drawn, %)	~70–80	~60–75	~65–75	~70–80
Tensile strength (MPa)	300–500	250–450	600–900	300–600
Elastic modulus (GPa)	3.5–4.9	3.5–5.0	3.5–5.5	5.0–10.0
Elongation at break (%)	15–80	10–25	100–200	5–25
Typical length (mm)	6–54	6–54	3–25	30–60
Surface energy (as produced)	Low, ~30 mN/m	Low, roughened by splitting	Low, high specific area	Low, ~30 mN/m
Role in concrete	Microcrack control	Crack control and bonding	Fresh-mix rheology	Structural load transfer

Fiber-grade PP is also formulated with a melt-flow index (MFI) suited to melt spinning; higher-MFI (lower-viscosity, typically lower-molecular-weight) resin spins more readily and at higher throughput, but conventional processing of high-MFI resin tends to yield lower-strength fiber unless a two-stage solid-state drawing route is used, which has been shown capable of raising tensile strength of an ultrahigh-MFI (115 g/10 min) PP to approximately 600 MPa with an elastic modulus near 12 GPa. Crystallinity in melt-spun PP fiber typically rises from roughly 50% in the as-spun state to 70–80% after hot drawing, driven by chain orientation and strain-induced crystallization; molecular orientation and the density of load-bearing tie-molecules connecting crystalline domains, rather than crystallinity alone, have been identified as the dominant determinants of fiber tensile modulus. Drawing ratio is, therefore, the single processing parameter with the largest direct influence on finished-fiber stiffness and strength: elastic modulus of melt-spun PP fiber has been reported to rise from approximately 5.3 GPa in the undrawn state to 6–8 GPa at a draw ratio of 10, with corresponding gains in tensile strength and creep resistance [5, 6].

Thermally, PP has a melting range of approximately 160–170 °C and undergoes thermo-oxidative degradation above this range in the presence of oxygen, a property directly relevant to fire behavior in concrete (Section 12). Commercial fiber-grade PP is stabilized with antioxidant packages (typically hindered phenols and phosphite co-stabilizers) to resist oxidation during melt processing and in service; stabilizer depletion over time is a primary long-term ageing mechanism (Section 12). PP fiber is manufactured by three principal routes: monofilament melt spinning, followed by drawing, yields round or quadrangular cross-section fibers with a smooth surface; film extrusion followed by mechanical splitting (fibrillation) yields a ribbon-like fiber with a rough, interconnected network morphology (Figure 2); and multifilament bundling of many fine filaments yields a high-specific-surface-area fiber used mainly to modify fresh-state rheology and control plastic-shrinkage cracking at the earliest curing stages [7]. These three morphologies, together with coarser macro-structural monofilament or twisted fiber, define the four fiber categories summarized in Table 1 and classified under EN 14889-2, and each processing route produces a distinct starting surface condition that carries directly into the interfacial behavior discussed in Section 5.

Structure → Processing → Interface → Performance framework for polypropylene fibres in cementitious composites

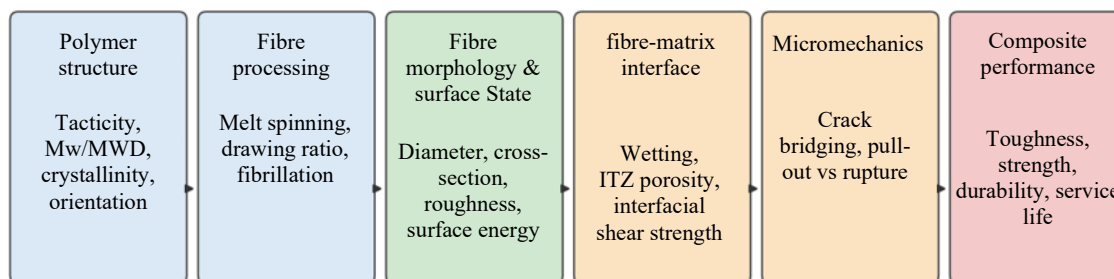


Figure 2. Structure-processing-interface-performance framework for polypropylene fibers in cementitious composites.

Virgin PP resin dominates current construction fiber supply, but mechanically recycled PP, typically reprocessed from post-consumer or post-industrial packaging waste, is of growing interest; recycled feedstock generally carries a broader MWD and a higher level of chain scission from prior thermal history, which tends to lower achievable draw ratio and hence fiber strength relative to virgin resin unless the recycled stream is blended with virgin polymer or compatibilized (Section 13).

Crystallinity values are representative ranges compiled from processing-structure studies on melt-spun and drawn iPP fiber [5, 6] rather than measurements on the specific commercial grades in Table 1; they are included to indicate typical order of magnitude rather than a manufacturer specification.

REVIEW SCREENING PROCESS

The screening process described in Section 2 is summarized as a three-stage funnel: 310 records identified across the three databases, 148 records retained for full-text assessment following title/abstract screening, and 55 records included in the final synthesis after full-text eligibility review.

POLYMER SURFACE CHEMISTRY AND THE POLYPROPYLENE-CEMENT INTERFACE

The single most consequential fact governing PP fiber performance in a cementitious matrix is that polypropylene is a nonpolar, hydrophobic polymer of low surface energy (approximately 30 mN/m), while cement paste is a polar, hydrophilic and strongly alkaline (pore-solution pH approximately 12.5–13.5) medium [6]. Untreated PP presents an advancing water contact angle in the region of 95–105 degrees, and Wilhelmy-plate measurements on untreated polypropylene fiber have reported advancing and receding contact angles of approximately 100 and 77 degrees, respectively, confirming poor wettability by aqueous and cementitious fluids alike. Because wetting is the necessary first step in developing any interfacial adhesion, this chemical incompatibility, not fiber geometry alone, is the root cause of the weak PP-cement bond repeatedly reported in the literature.

In the absence of chemical bonding, three physical mechanisms govern stress transfer across the PP-cement interfacial transition zone (ITZ): (i) frictional resistance along the fiber–matrix contact area, which depends on fiber surface roughness and residual clamping stress from matrix shrinkage around the fiber; (ii) mechanical interlocking, which is negligible for smooth monofilament fiber but substantial for fibrillated, embossed, crimped or twisted geometries; and (iii) fiber pull-out versus fiber rupture as the terminal failure mode, with pull-out dominating for smooth, low-modulus PP fiber embedded at typical construction lengths, and rupture becoming more likely only for well-bonded, short-embedment or highly roughened fiber. Elastic-modulus mismatch compounds the adhesion problem: the modulus of PP (approximately 2–5 GPa, Table 1) is roughly an order of magnitude below that of the surrounding hardened cement paste (approximately 20–35 GPa), so under load the fiber strains more than the matrix immediately around it, promoting interfacial debonding and slip even where some frictional or mechanical anchorage exists [8].

Shrinkage of the cement paste during hydration further widens the micro void annulus around the fiber, reducing the effective contact area and hence the achievable frictional bond. SEM examination of pull-out specimens consistently shows untreated PP fiber surfaces largely free of adhered hydration product after extraction, in contrast to surface-modified fiber, where residual calcium–silicate–hydrate (C–S–H) and portlandite are visibly retained on the extracted surface, indicating a genuine change in adhesion mechanism rather than only a change in surface roughness [8, 9]. Single-fiber and double-fiber pull-out testing, fiber fragmentation testing, and dynamic pull-out under controlled loading rate are the principal experimental methods used to quantify interfacial shear strength for PP fiber systems, complemented by SEM and, less commonly, atomic force microscopy (AFM), Fourier-transform infrared spectroscopy (FTIR) and X-ray photoelectron spectroscopy (XPS) to characterize the chemical and topographic state of the fiber surface before and after treatment or pull-out [9].

Mechanistically, the chain of causation for PP fiber reinforcement can be summarized as: polymer chemistry sets surface energy, which governs wetting, which controls the degree of interfacial adhesion achievable, which determines the efficiency of stress transfer across the ITZ, which in turn governs crack-bridging capacity and, at the composite scale, post-cracking toughness. This framework (Figure 2) is used throughout the remainder of this review to connect polymer-level variables to composite-level outcomes, rather than treating dosage as the only design variable, as is common in concrete-performance literature.

Taken together, these polymer-, processing- and surface-level variables do not act independently: fiber category (Table 1) fixes the manufacturing route and hence the as-produced surface morphology, Isotacticity and drawing ratio (Section 3) fix the crystallinity and modulus ceiling the fiber carries into the mix, and it is only at the point of contact with cement paste that these upstream choices are expressed as a measurable interfacial outcome. A high-modulus, low-surface-energy monofilament fiber and a rougher, higher-surface-area fibrillated fiber spun from the same resin can present markedly different pull-out behavior despite identical bulk polymer chemistry, because processing history determines surface roughness and specific areas independently of molecular weight or crystallinity. Conversely, two fibers of similar morphology but different molecular weight distribution will differ in modulus mismatch with the surrounding paste (Section 5), and hence in the strain compatibility that governs whether friction or debonding dominates at the interface. This collective, rather than additive, dependency is the reason Section 8 examines mechanical performance as a function of fiber morphology, surface condition, aspect ratio and dispersion quality together, rather than attributing composite-level gains to dosage or to any single polymer variable in isolation.

Multi-Scale Crack Bridging

Crack bridging, the capacity of a fiber spanning a propagating crack to transmit tensile stress across the crack faces and, thereby reducing the stress intensity at the crack tip, is the mechanism through which interfacial adhesion (Section 5) is translated into composite-level performance. It operates at two distinct scales corresponding to the fiber categories in Table 1: microfibers (diameter 6–40 μm) interact with the cement paste and mortar matrix at the pore and capillary-crack level, arresting the coalescence of distributed microcracks before they widen into macrocracks, while fibers of diameter greater than approximately 300 μm engage with cracks that have penetrated the mortar matrix and are propagating through the mortar–aggregate interface [10, 11].

Bridging action has a pre-crack and a post-crack phase. In the pre-crack phase, load sharing between matrix and fiber is governed by stress transfer at the interface described in Section 5, and depends on fiber volume fraction, aspect ratio and interfacial bond quality. Once matrix tensile strength is exceeded and the first crack forms, the post-crack phase begins: fibers bridging the crack sustain tensile transfer through elastic stretching, frictional pull-out resistance and, where present, mechanical interlock (Figure 3). This sustained load transfer produces the characteristic gains in toughness, ductility and post-cracking energy absorption reported for PP-FRC [12].

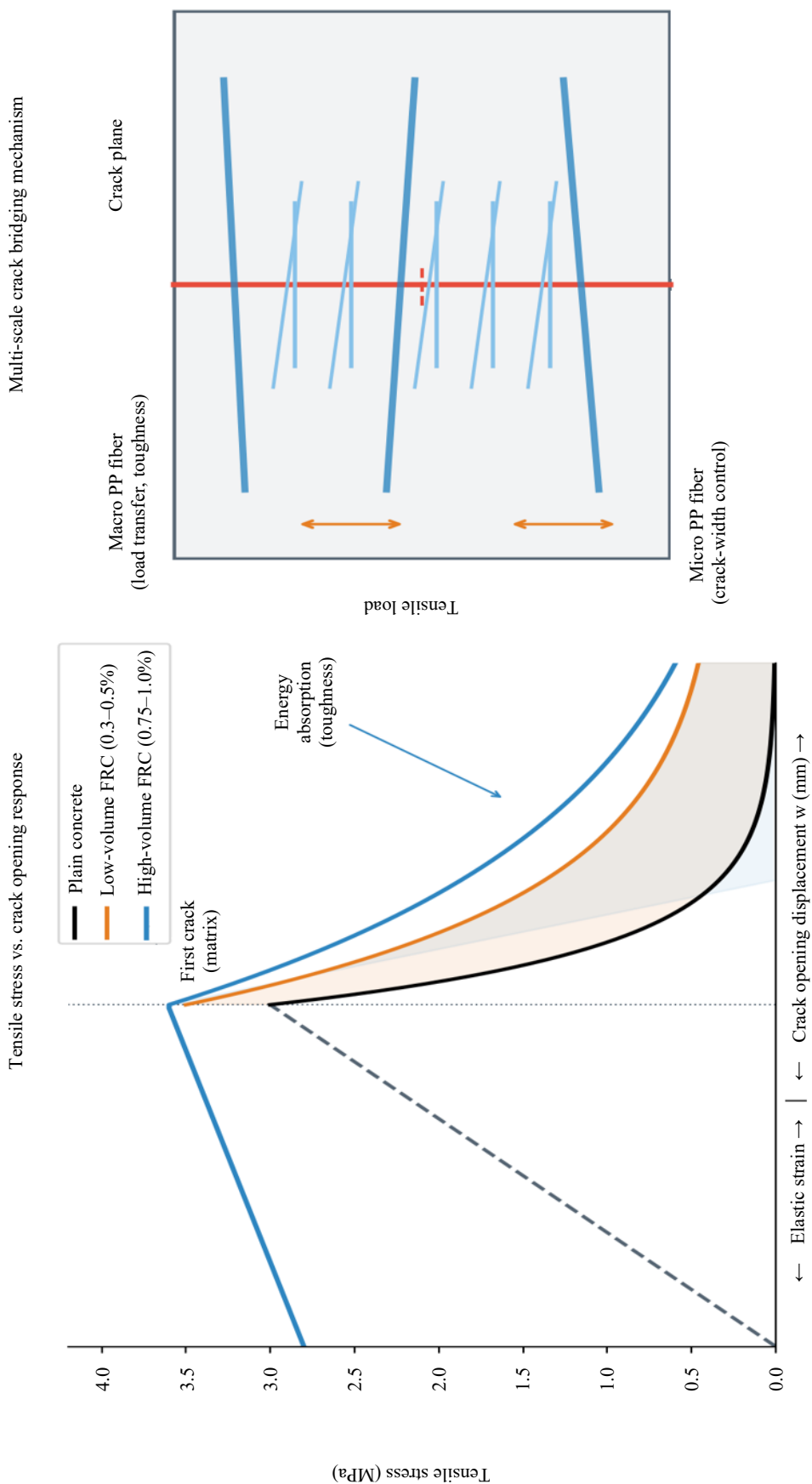


Figure 3. Multi-scale crack bridging in PP fibre-reinforced concrete: tensile stress response and schematic mechanism.

SURFACE MODIFICATION AND FUNCTIONALIZATION OF PP FIBERS

Because the untreated PP-cement interface is adhesion-limited rather than geometry-limited, a substantial body of polymer-composites literature has addressed surface modification of PP fiber to improve wetting and, where possible, introduce chemical or hydrogen bonding with the cement hydration products. Table 2 summarizes the principal methods.

Table 2. Surface-modification methods for PP fibers in cementitious composites.

Treatment	Mechanism	Reported effect	Alkaline durability evidence	Reference
Plasma (SiCl ₄ , DBD)	Introduces polar Si/O groups; physical etching	Contact angle $\sim 100^\circ \rightarrow \sim 66^\circ$; improved pull-out bond in polyolefin fiber	Not systematically reported	[13]
Corona / UV-ozone	Surface oxidation	+ $\sim 20\%$ pull-out deformation energy vs untreated	Limited data	[6]
Chemical (oxyfluorination)	Introduces C=O, C–OH groups	Wetting index + $\sim 30\%$ (29 $\rightarrow$ 38 dyn/cm)	Not reported	Patent literature (not peer-reviewed; cited for mechanism only)
Alkaline treatment	Introduces soda-based protrusions; nucleates portlandite/ettringite	Combined chemical + mechanical adhesion gain	Inherently alkaline-stable (treatment itself alkali-based)	[6]
Silane coupling	Siloxane network; H-bonding with hydration products	Roughened surface; improved sulfate resistance (magnitude smaller than wettability gain alone)	Partial evidence (sulfate study)	[14]
Maleic-anhydride grafting	Polar –COOH groups; H-bonding with C–S–H	Up to $\sim 450\%$ IFSS gain in PP-matrix composite (non-cementitious benchmark)	Not reported for cementitious systems	[15]
Nano-silica / cementitious slurry coating	Promotes C–S–H nucleation at fiber surface	Reduced ITZ porosity; improved chemical adhesion	Not systematically reported	[16]
Mechanical embossing/fibrillation	Physical interlock, independent of chemistry	Increases mechanical bond component; additive to chemical treatment	Durable by definition (geometric, not chemical)	[10]

Plasma and Corona Treatment

Low-temperature plasma (including dielectric-barrier-discharge and SiCl₄-plasma treatments) and corona discharge introduce polar oxygen- or silicon-containing functional groups onto the PP surface without altering bulk fiber properties. Plasma treatment of PP with SiCl₄ has been reported to reduce the advancing contact angle from approximately 100 degrees (untreated) to approximately 66 degrees, a substantial improvement in wettability confirmed by ESCA (XPS) analysis of surface chemistry. Similar dielectric-barrier-discharge plasma treatment of polyoxymethylene fiber for cement reinforcement has been shown to introduce hydroxyl groups at the surface and measurably improve fiber-cement pull-out bond strength, illustrating the same mechanism as applied to a chemically comparable polyolefin-type fiber [13]. Corona and UV/ozone treatment act through a related oxidative mechanism; pull-out testing on PP macrofiber treated by UV-LED exposure and by corona discharge has shown increased peak pull-out load and deformation energy relative to untreated fiber, with deformation energy in cement-based mortar reported to increase by roughly 20% for treated fiber [6].

Chemical Oxidation and Alkaline Treatment

Oxyfluorination and related gas-phase oxidation treatments reduce contact angle and increase the acid-base component of PP surface free energy; patent literature reports wetting indices rising from approximately 29 dyn/cm (untreated) to 38 dyn/cm or higher (oxidized), a roughly 30% increase, with corresponding improvement in cement-paste wetting. Alkaline surface treatment has been shown by

FTIR and XPS to introduce carboxyl, carbonyl, hydroxyl and ester functional groups at the fiber surface, and alkaline treatment specifically has been reported to introduce soda-based surface protrusions that both roughen the fiber and act as nucleation sites for portlandite and ettringite growth directly on the fiber surface, combining a chemical and a mechanical adhesion benefit [6].

Silane Coupling and Maleic-Anhydride Grafting

Silane coupling agents (commonly amino- or epoxy-functional silanes) form a siloxane network at the fiber surface capable of hydrogen bonding, and in some cases covalent linkage, with hydration products; silane-treated PP fiber used in cement mortar sulfate-resistance testing showed a measurably roughened surface after treatment together with improved corrosion resistance under sulfate exposure, though the same study noted the sulfate-resistance benefit was smaller than the wettability improvement alone would suggest, illustrating that contact-angle reduction does not always translate proportionally into a durability benefit [14]. Maleic-anhydride grafting (typically 0.1–3.0 wt% anhydride content grafted onto the PP backbone during melt processing) introduces polar carboxylic-acid groups capable of hydrogen bonding with C–S–H gel; a two-step treatment combining electrochemical oxidation with subsequent silane treatment on carbon fiber embedded in a maleic-anhydride-grafted PP matrix has been shown to raise interfacial shear strength by approximately 450% relative to untreated fiber, illustrating the upper bound of what combined surface chemistry and coupling-agent strategies can achieve in a PP-based interface, although this magnitude of improvement was obtained for a carbon-fiber/PP-matrix composite rather than a PP-fiber/cement-matrix system and should be read as an upper-bound reference point rather than a direct prediction for construction-grade PP fiber [15].

Mineral and Cementitious-Slurry Coating

Nano-silica sol-gel coatings and cementitious-slurry pre-coating of macro-PP fiber surfaces have been shown to promote C–S–H nucleation directly at the fiber surface, improving chemical adhesion and reducing the interfacial porosity that otherwise characterizes the untreated ITZ [16].

Mechanical Embossing and Fibrillation

Independent of surface chemistry, physical roughening (embossing, crimping, twisting or fibrillation) increases the mechanical-interlock component of bond strength; optical imaging of chemically treated fiber has shown that some chemical treatments alter contact angle without measurably changing surface roughness, confirming that the chemical and mechanical contributions to bond improvement are separable and, where combined, are expected to be at least partly additive [6].

For every treatment summarized above, the evidence is reported here as a change in contact angle, pull-out load or interfacial shear strength relative to an untreated control, consistent with the editorial guidance against asserting that a treatment “improves bonding” without quantitative or mechanistic support. Durability of these treatments under sustained alkaline exposure, the condition the fiber actually experiences in service, is markedly less well characterized in the literature than the initial as-treated bond improvement and is identified in Section 15 as a priority research gap.

Table 2 shows that these methods differ sharply in maturity of evidence rather than only in mechanism. On initial bond improvement, plasma and Oxyfluorination treatments produce the largest documented shifts in wettability (contact-angle and wetting-index changes of 30–35%), silane coupling and alkaline treatment produce moderate, chemically anchored gains that are also mechanically reinforced through surface roughening and maleic-anhydride grafting shows the largest reported interfacial-shear-strength gain but only in a non-cementitious benchmark system, so it cannot yet be ranked directly against the others for PP-cement bond. On long-term alkaline durability, the evidence base is far less even, i.e., alkaline treatment is durable by construction, since the treatment itself is alkali-based and cannot be undone by further alkaline exposure. Mechanical embossing and fibrillation are similarly durable because the bond gain is geometric rather than chemical and cannot degrade chemically, but plasma, corona/UV-ozone, Oxyfluorination, silane coupling and mineral coatings all

report only as-treated bond data, with sustained alkaline-exposure testing either absent or limited to a single study. Ranked by the combination of demonstrated effectiveness and demonstrated alkaline durability, alkaline surface treatment and mechanical roughening are, therefore, the two approaches best supported for near-term specification, while plasma, silane and mineral-coating strategies remain promising on initial bond evidence alone but require the long-term alkaline-immersion pull-out testing identified in Section 15 before their comparative durability can be established with confidence.

DISPERSION, PROCESSING AND FRESH-STATE RHEOLOGY

The addition of PP fibers measurably change fresh concrete rheology, and the magnitude of the change depends primarily on fiber volume fraction and geometry rather than on any single mix parameter in isolation. At low dosage (0.25–0.75% by volume), fiber addition produces a moderate reduction in slump, typically 5–15% relative to an unfibered control, while improving cohesion and reducing susceptibility to segregation and bleeding. As fiber volume fraction approaches or exceeds 1.0%, the increased fiber surface area raises the paste demand needed to coat all fibers, increasing plastic viscosity and yield stress; at 1.5% by volume, slump reductions of 30–65% have been reported, and at 2.0% without compensating admixtures, slump can approach zero (Figure 4). Polycarboxylate-ether (PCE) superplasticizers partially restore workability through steric dispersion of cement particles and reduced fiber–fiber friction, but there is a practical limit beyond which superplasticizers dosage cannot fully compensate for excessive fiber volume, and fiber balling becomes increasingly likely beyond this threshold, producing zones of concentrated fiber separated by fiber-poor concrete with markedly non-uniform mechanical properties [17–20]. The two-stage mixing approach (TSMA), in which dry constituents and a portion of the mixing water are combined first to achieve preliminary particle distribution before fibers are introduced, has been identified as a practical process-engineering solution that substantially improves fiber dispersion without requiring a change to concrete composition [21].

Table 3. Effect of PP fiber dosage on fresh concrete properties.

Fresh property	Low dosage (0.25–0.75% vol.)	High dosage (>1.0% vol.)	Key mechanism	References
Workability (slump)	Slight reduction (5–15%); cohesion improved	Severe slump loss (30–65%); near-zero at 2% vol.; balling risk	Increased surface area raises yield stress	[22, 23]
Plastic viscosity	Marginal increase; manageable with PCE superplasticizers	Sharp rise; forced vibration needed; poor SCC compatibility	Fiber–fiber friction in fresh matrix	[19, 24]
Air content	Minimal change (<0.5% increase)	Air-void content rises 1–3%; entrapped voids increase porosity	Fiber network traps air during mixing	[7, 25]
Setting time	Slight delay (15–30 min); no strength loss	Prolonged set; early-strength reduction risk	Fibers modify free-water availability	[26, 27]
Water absorption	Reduced 10–20% (matrix densification)	Increased capillary absorption; higher fiber surface area wicks water	Hydrophobic PP surface vs capillary action	[28, 29]
Admixture synergy	Strong: PCE restores workability up to 3x gain	Partial: admixtures cannot fully offset excessive fiber volume	Steric dispersion by PCE	[13, 19]

The hydrophobic character of polypropylene, combined with the high specific surface area of fine microfiber, produces a genuinely two-sided effect on water-related fresh-state behavior. In engineered cementitious composites and high-performance mixes, PP fiber addition has been shown to reduce capillary porosity and water absorption through mechanical densification of the paste microstructure around the fiber during hydration (Table 3). In conventional mixes without careful water control, the same high fiber surface area can instead act as a site for localized water retention, slowing hydration kinetics and delaying initial set by approximately 15–30 minutes, with corresponding relevance for precast operations that depend on early demolding [27, 29].

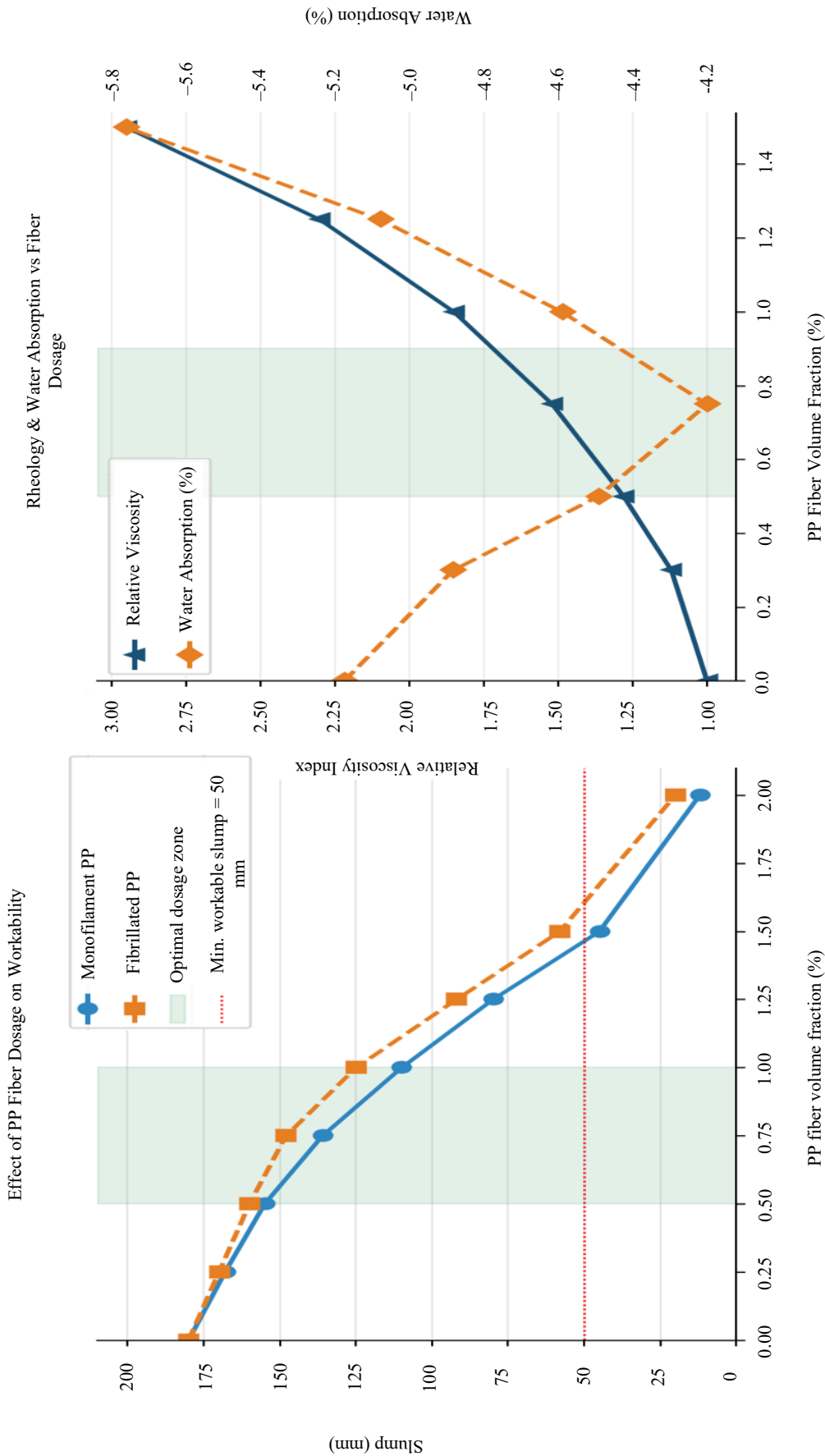


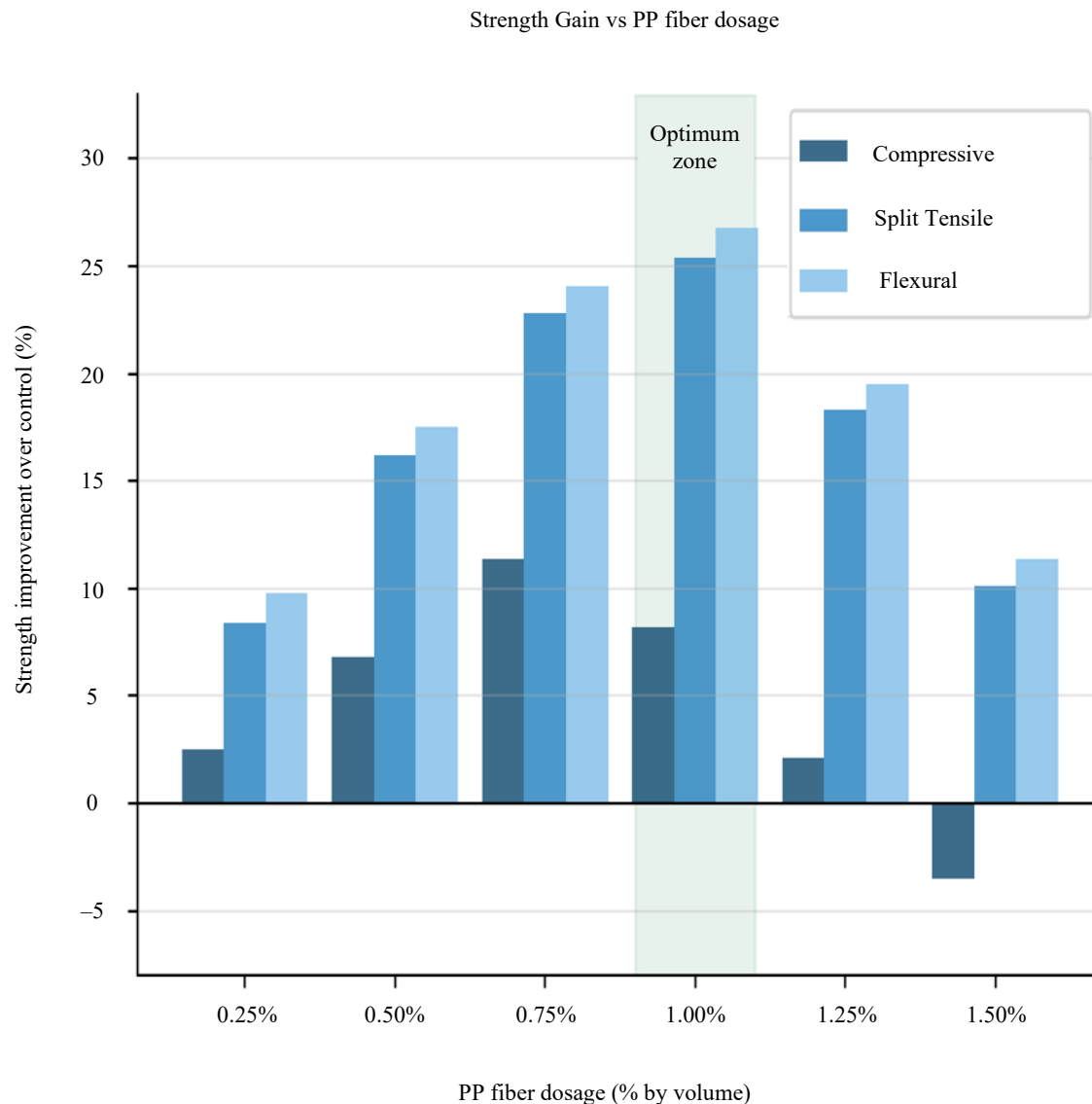
Figure 4. Effect of PP fiber dosage on workability (slump), relative viscosity and water absorption of fresh concrete.

STRUCTURE-PROPERTY RELATIONSHIPS: MECHANICAL AND FRACTURE PERFORMANCE

Consistent with the interfacial framework in Section 5, mechanical performance gains from PP fiber addition are examined here as a function of polymer- and composite-level variables (fiber morphology and surface condition, aspect ratio, dispersion quality and volume fraction) rather than dosage alone.

Compressive Strength

Reported compressive-strength changes with PP fiber addition are modest and, unlike tensile and flexural gains, are not consistently positive: gains of 5–12% relative to plain concrete have been reported at optimal dosages of 0.5–0.75% by volume, attributed to improved cohesion resisting matrix separation under compression, but gains reverse to a slight reduction once fiber content exceeds approximately 1.0–1.25% by volume as entrapped air and reduced compaction quality reduce effective cross-sectional density [30]. Individual studies report a wide range of absolute values depending on base mix design; for example, one study reported an 18.8% compressive-strength gain at 1.0% PP fiber (27.67 to 32.89 MPa), while another reported an optimum of 38.12 MPa at 0.75% fiber content in an M30-grade mix, confirming that the fiber-content/compressive-strength relationship is non-monotonic and mix-dependent rather than governed by fiber content in isolation (Figure 5).



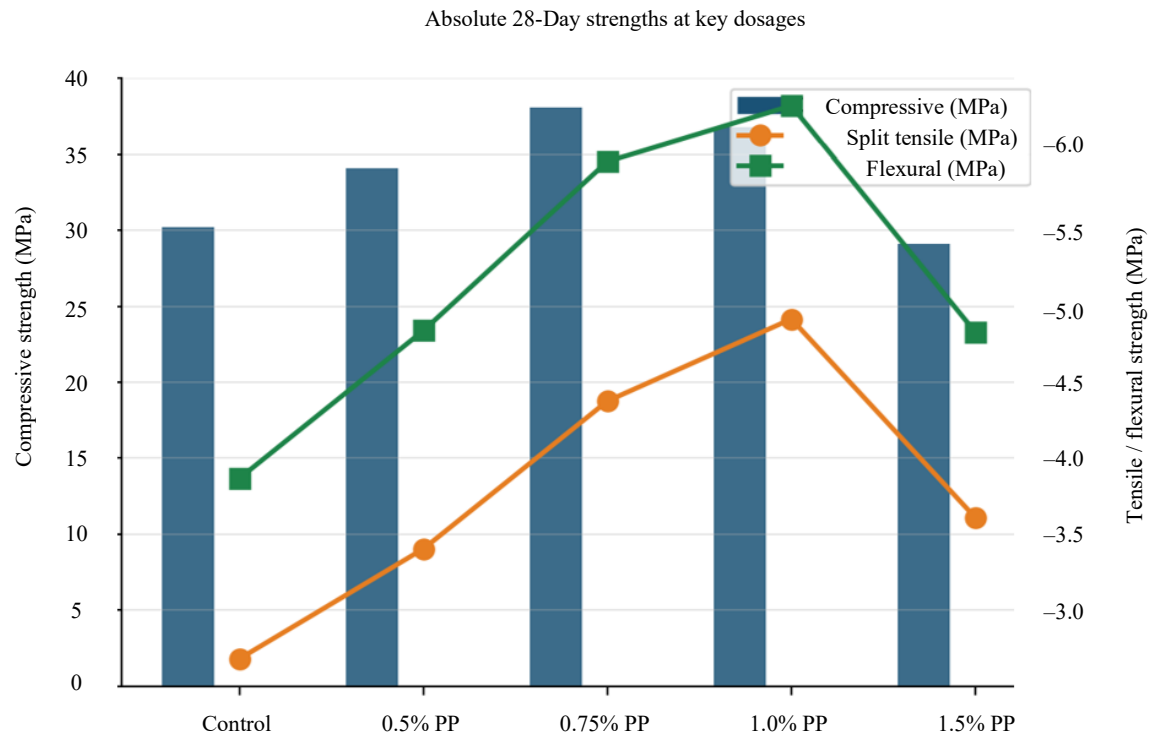


Figure 5. PP fiber dosage effects on concrete strength percentage gain (left) and absolute 28-day values (right).

Tensile and Flexural Strength

PP fibers exert their most substantial and consistent positive influence on tensile and flexural properties, consistent with the crack-bridging mechanism of Section 5.1, which is particularly effective in resisting mode-I crack opening under bending and splitting loads. Across the reviewed dataset, split tensile strength improvements at 0.75–1.0% volume fraction falls consistently in the range 18–28% relative to plain-concrete controls, while flexural-strength improvements of 20–30% are routinely documented [31–33]. This improvement is further enhanced by supplementary cementitious materials (SCMs): a mix combining 1.0% PP fiber with 10% metakaolin and 20% fly ash achieved 45.6 MPa compressive strength, substantially higher than either the fiber-only or SCM-only mixes, together with superior tensile and flexural performance, reflecting the microstructure-densifying role of pozzolanic SCMs in filling ITZ porosity that would otherwise limit interfacial stress transfer (Table 4).

Table 4. Comparative strength performance of PP and other fiber types at reported dosages.

Fiber type	Dosage (%)	Aspect ratio	Compressive strength gain (%)	Tensile strength gain (%)	Flexural strength gain (%)	Reference
PP monofilament	0.5	54	+6.8	+16.2	+17.5	[34]
PP monofilament	0.75	54	+11.4	+22.8	+24.1	[32]
PP fibrillated	0.5	48	+8.5	+18.0	+20.3	[35]
PP macro fiber	1.0	65	+5.2	+25.4	+26.8	[31]
Polyolefin fiber	1.0	60	+12.0	+18.5	+24.5	[36]
Steel fiber (hooked)	0.5	80	+15.2	+30.4	+32.5	[37]
PVA fiber	2.0	450	+4.8	+28.6	+22.1	[38]
Basalt fiber	0.5	55	+9.2	+20.5	+23.8	[39]

Post-Cracking Toughness and Ductility

PP fiber addition significantly increases the energy that concrete beams absorb prior to failure, as quantified by the area beneath the load-deflection or stress-crack-opening curve under both peak-load-strength and energy-absorption test protocols. Beams containing PP fiber show greater absorbed energy and a longer time to failure under repeated dynamic loading than plain-concrete controls, consistent with gradual, ductile failure rather than sudden brittle fracture. This property is directly relevant to applications in seismic-resistant, blast-resistant and high-impact industrial elements, where energy absorption and redistribution matter more than peak strength alone.

THERMAL, CHEMICAL AND ENVIRONMENTAL AGEING OF PP FIBERS

Durability discussion in the PP-FRC literature has tended to conflate three distinct phenomena, which this review deliberately separates: (i) durability of the polypropylene fiber itself as a polymer; (ii) durability of the fiber–matrix interface; and (iii) durability of the cementitious composite. All three are influenced by the same environmental exposures but respond through different mechanisms and at different rates.

Thermal and Oxidative Ageing of the Fiber

PP undergoes thermo-oxidative degradation above its melting range (approximately 160–170 degrees C), with antioxidant depletion as the rate-limiting step in service-temperature ageing; once stabilizer reserves are exhausted, unprotected chain oxidation proceeds via a well-characterized radical mechanism, producing chain scission, embrittlement and loss of elongation at break, with crystallinity often increasing as shorter chain segments crystallize more readily even as overall toughness falls. Embrittlement of PP fiber during thermal oxidation has been documented as a distinct failure mode from simple melting, relevant to PP fiber embedded near a concrete surface exposed to sustained elevated temperature well below the polymer melting point [35].

Alkaline Exposure

Cement pore solution is strongly alkaline (pH approximately 12.5–13.5); while PP itself is chemically inert to hydrolysis (unlike ester-based synthetic fibers, such as polyester, which are documented to degrade in alkaline environments via hydrolytic scission of ester linkages, a vulnerability PP does not share), sustained alkaline exposure has nonetheless been shown to progressively degrade the fiber-matrix bond rather than the fiber bulk, consistent with the interfacial rather than bulk-polymer locus of alkaline attack on PP-FRC durability [16].

Freeze-Thaw and Combined Alkali-Freeze-Thaw Effects

Freeze-thaw cycling acts primarily on the interface and the surrounding matrix rather than on the PP fiber bulk: water present in microcracks near the fiber expands during freezing, and where crack-bridging force is insufficient, microcracks propagate into macrocracks. Combined alkali-aggregate and freeze-thaw exposure has been shown experimentally to be more damaging than either mechanism alone, with reported reductions in compressive strength of up to approximately 35%, flexural strength of up to approximately 33%, and residual strength of up to approximately 97% at high alkali-aggregate content combined with freeze-thaw cycling, alongside increased mass loss and reduced dynamic modulus of elasticity [36].

UV Degradation

For fiber exposed near the concrete surface (as opposed to fully embedded fiber, which is effectively UV-shielded by the surrounding matrix), UV radiation initiates photo-oxidative chain scission analogous to the thermal-oxidative mechanism above, producing surface microcracking, discoloration and reduced elongation at break; this mechanism is well documented for PP-based composites generally but has been investigated less specifically for construction-grade PP fiber embedded at or near a concrete surface than for thermal and alkaline exposure, and is identified in Section 14 as a research gap.

Creep, Stress Relaxation and Long-Term Pull-out Behavior

As a viscoelastic polymer, PP fiber is subject to creep and stress relaxation under sustained load, which can gradually reduce the effective clamping and frictional-bond contribution to pull-out resistance over time; this behavior has been studied for cracked PP-FRC under uniaxial tensile creep and is a factor distinguishing long-term crack-bridging capacity from the short-term pull-out values typically reported in the interfacial literature [40].

Ageing of Recycled PP Fiber

Recycled PP feedstock typically carries prior thermal and oxidative history from an earlier service life, which can leave the resin closer to the onset of embrittlement than virgin resin at the point of fiber manufacture, making stabilizer-package selection and blending ratio with virgin resin particularly important for recycled-content fiber intended for long-service-life structural use.

Microplastic and Fiber-Release Considerations

Cutting, crushing and demolition of PP-FRC elements can release PP fiber fragments and microplastic particles into the environment; this end-of-life and demolition-stage impact is distinct from, and additional to, the production-stage embodied-carbon impact more commonly discussed in the sustainability literature and is presently under-quantified for construction-grade PP fiber specifically (Table 5).

Table 5. Polymer ageing mechanisms affecting PP fiber-reinforced concrete.

Ageing mechanism	Locus of action	Observable change	Composite-level consequence	Reference
Thermal/oxidative	Fiber bulk (above ~160–170°C, or below with antioxidant depletion)	Chain scission; embrittlement; falling elongation at break	Loss of crack-bridging ductility in heat-exposed elements	[35]
Alkaline exposure	Fiber–matrix interface	Bond degradation (fiber bulk largely inert)	Reduced pull-out resistance over service life	[16]
Freeze-thaw (+alkali)	Interface and surrounding matrix	Microcrack expansion; dynamic modulus loss	Up to ~35% compressive, ~33% flexural strength loss (combined exposure)	[36]
UV exposure (surface fiber only)	Fiber surface	Photo-oxidative chain scission; discoloration	Localised surface microcracking near exposed fiber	General polymer ageing literature
Creep/stress relaxation	Fiber bulk and interface	Reduced clamping/frictional bond over time	Long-term crack-bridging capacity below short-term pull-out value	[16]

RECYCLED PP FIBERS AND LIFE-CYCLE CONSIDERATIONS

The environmental profile of PP fiber reinforcement is more nuanced than “non-corroding, therefore, sustainable” framings sometimes suggest, and is assessed here quantitatively against alternative fiber types rather than asserted qualitatively. On a per-kilogram production basis, PP resin manufacture has been estimated at approximately 1.58 kg CO₂-eq per kg of PP produced. Because PP is far less dense than steel and is used at much lower dosage by mass, however, comparative studies using a volume-of-concrete functional unit (1 m³ of fiber-reinforced concrete) find the fiber-type choice makes comparatively little difference to overall global-warming potential once cement production is accounted for: one comparative life-cycle assessment reported global-warming values of approximately 373 kg CO₂-eq for 1 m³ of concrete with 0.25% PP fiber, against approximately 392 kg CO₂-eq for glass fiber, 384 kg CO₂-eq for basalt fiber and 382 kg CO₂-eq for steel fiber at the same volume fraction, a spread of under 5% across fiber types and small relative to the emissions contribution of the cement itself [41]. A separate shear-strength and life-cycle comparison similarly found that, once fiber mass rather than fiber volume is used as the functional unit, PP’s low density gives it the lowest environmental-cost-indicator value among the fiber types compared, while steel fiber’s low per-kilogram impact is offset by the roughly nine-times-greater mass of steel required for an equivalent volume fraction [42]. These findings indicate that fiber-type selection for embodied-carbon reasons should be made on a volume-

of-concrete or component basis rather than a per-kilogram-of-fiber basis, since the two functional units can rank the same fibers differently.

Virgin PP fiber currently dominates construction supply, but recycled PP fiber sourced from post-consumer or post-industrial packaging waste has been shown capable of achieving comparable mechanical performance to virgin PP fiber at dosages up to approximately 0.5% by volume, while reducing the embodied carbon of the concrete mix [25, 43]. Recycling infrastructure specifically for construction-grade PP fiber, as distinct from PP packaging generally, remains limited in most regions, and end-of-life separation of PP fiber from hardened concrete for recovery is not currently practiced at scale; demolished PP-FRC is presently landfilled, crushed for aggregate reuse (with fiber remaining embedded), or, in principle, incinerated with energy recovery, and each of these end-of-life pathways carries distinct and under-quantified environmental trade-offs, including the microplastic-release concern noted in Section 12. Life-cycle assessment evidence suggests that the service-life extension achievable through PP fiber crack control, principally via reduced chloride ingress and mitigated surface spalling, can offset the initial production-stage environmental cost of fiber manufacture over a structure's design life of 50–100 years, but this offset should be understood as a service-life argument rather than as evidence that PP fiber production itself is low-impact.

ENGINEERING APPLICATIONS

Polypropylene fiber reinforcement is applied across pavements, industrial flooring, precast elements, tunnel linings and impact-resistant structures, and this section is retained as evidence of how the structure-processing-interface-performance chain established in Sections 3–9 translates into field performance, rather than as the review's principal contribution (Table 6).

Table 6. PP fiber applications: typical dosage, role, and reported performance.

Application area	Typical dosage (% vol.)	Primary role of PP fiber	Key reported improvements	Reference
Rigid pavements (PQC)	0.5–0.8	Micro-crack arresting; plastic-shrinkage control	Compressive +10–18%; flexural +20–30%; plastic shrinkage largely eliminated	[44]
Flexible pavements (asphalt)	0.3–0.6	Tensile reinforcement; rut resistance	Marshall stability +15–20%; rut depth –30%	[45]
Industrial flooring	0.6–1.0	Crack control; abrasion resistance	Compressive 38→46 MPa; abrasion resistance +40%; maintenance cost –50%	[46]
Precast concrete elements	0.5–0.8	Structural reinforcement; handling resilience	Compressive and flexural strength +25%; reduced demoulding cracking	[47]
Tunnel segments and linings	0.8–1.25	Replacement of conventional steel reinforcement; corrosion immunity; fire spalling mitigation	Enhanced crack resistance; zero corrosion risk; reduced labor cost	[28, 48, 49]
Impact-resistant structures	1.0–1.5	Energy absorption; post-cracking ductility	Impact energy absorbed +35–50%; flexural toughness >50 J	[2, 50]
Shield tunnel structures	0.75–1.0	Load-bearing under deformation; moisture resistance	Reduced structural failure risk; superior long-term durability	[51]

In pavement-quality concrete, PP fiber addresses plastic-shrinkage cracking during construction and fatigue-induced cracking under repeated wheel loading, with reported compressive-strength gains of 10–18% and flexural gains of 20–30% at dosages of 0.5–0.8% by volume, and plastic-shrinkage crack-area reductions exceeding 75% in outdoor exposure. Hybrid PP-steel fiber systems have been shown to produce flexural-toughness values exceeding 50 J, a threshold associated with bridge-deck-overlay and airport-apron performance requirements [42, 45]. In industrial flooring, PP fiber at 0.6–1.0% by volume

is used as a labor-saving alternative to welded-wire mesh, with reported abrasion-resistance gains of approximately 40% and maintenance-cost reductions of up to 50% relative to conventionally reinforced slabs [40, 52].

In precast elements and tunnel linings, PP microfiber is used as a complementary or alternative reinforcement to steel rebar in tunnel segments, wall panels and roof slabs, reducing corrosion risk, improving production efficiency and easing handling during transport (Figure 6) [48, 49]. PP fiber is particularly valued in tunnel linings exposed to fire risk: unlike steel fiber, which has high thermal conductivity and expands differentially with the surrounding concrete, PP fiber melts at approximately 160 degrees C, creating a network of fine channels that vent steam pressure generated by rapid heating within the concrete mass, a spalling-mitigation mechanism now a standard design provision in fire-risk tunnel environments (Table 7) [48].

Table 7. Average strength and durability metrics for PP fiber applications.

Application	PP dosage (% vol.)	Avg. compressive strength (MPa)	Avg. flexural strength (MPa)	Shrinkage reduction (%)	Service-life increase (%)
Rigid pavements	0.65	45.85	5.85	55–75	15–20
Industrial flooring	0.80	47.40	6.10	40–60	20–30
Precast elements	0.65	48.60	7.05	30–50	18–25
Tunnel linings	1.00	56.25	7.25	45–65	25–35
Impact-resistant structures	1.25	55.35	7.65	50–70	20–30
Bridge decks (hybrid)	0.90	51.20	6.80	60–75	20–28

PP fiber application performance map (bubble size x flexural strength)

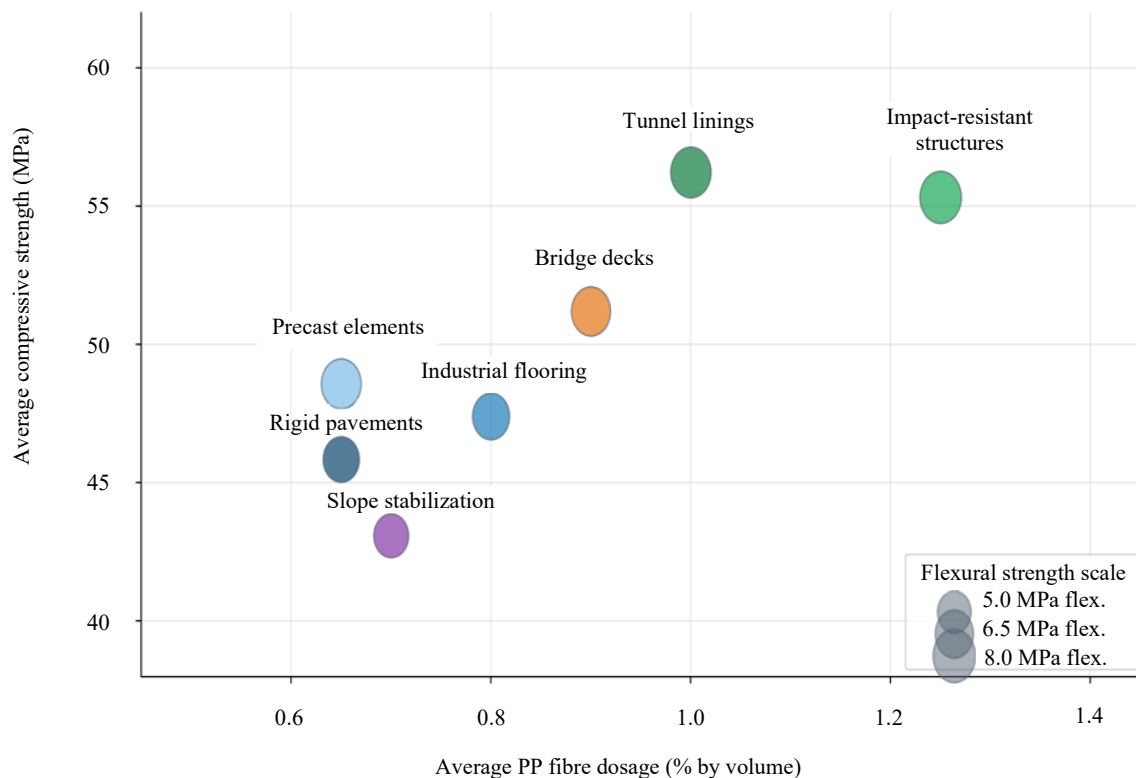


Figure 6. PP fiber application performance map: compressive strength vs dosage (bubble size proportional to flexural strength).

Comparative Fiber Assessment

No single fiber type is superior across all performance dimensions (Table 8). Steel fiber provides the highest tensile strength (1000–2000 MPa) and is generally preferred for primary structural reinforcement, but its susceptibility to chloride-induced corrosion limits use in marine and de-icing-salt environments, where PP fiber's corrosion immunity is a genuine advantage. Basalt fiber offers a high tensile-strength-to-weight ratio and, in alkali-resistant grades, good long-term alkali resistance with lower embodied carbon than glass fiber. Natural fibers (sisal, coir, jute) offer strong sustainability credentials through biodegradability and low embodied carbon, but their low mechanical strength, high moisture sensitivity and inconsistent quality currently confine their use to non-structural applications [37, 53, 54].

Table 8. Comparative assessment of PP fibers and alternative fiber reinforcement types.

Property	PP fiber	Steel fiber	Glass fiber (GFRP)	Natural fibers (sisal/coir)	Basalt fiber
Tensile strength	Moderate (300–600 MPa)	Very high (1000–2000 MPa)	High (700–1700 MPa)	Low (100–500 MPa)	High (800–1500 MPa).
Unit weight	0.91 g/cm ³ (very light)	7.85 g/cm ³ (heavy)	2.54 g/cm ³	1.2–1.5 g/cm ³	2.65 g/cm ³ .
Corrosion resistance	Excellent	Susceptible to chloride attack	Excellent	Susceptible to moisture degradation	Excellent (AR grade).
Relative cost	Low (USD 1.5–3/kg)	USD 1–6/kg (type-dependent)	High (USD 4–8/kg)	Very low	Moderate-high (USD 3–6/kg).
Fire/spalling resistance	Excellent (melts, vents steam)	Poor (thermal expansion mismatch)	Good	Poor (combustible)	Good (~1450°C melting point).
Sustainability	Fossil-derived; recyclable; low volume-basis GWP difference vs alternatives	Recycled-steel options available; high embodied energy	High embodied energy	Biodegradable; renewable	Inorganic; lower embodied energy than glass.

RESEARCH GAPS AND DESIGN FRAMEWORK

Building on the mechanistic discussion in Sections 5–10, this section synthesizes the outstanding limitations of the current evidence base and their implications for design guidance, supplemented by the severity assessment in Table 9. The most persistent fundamental limitation remains the weak PP-cement interfacial bond described in Section 5: unlike steel fiber, which develops both frictional and chemical adhesive forces, smooth PP fiber relies almost entirely on friction and mechanical interlock, and this bond can degrade further under sustained alkaline exposure or thermal cycling. Surface-modification techniques (Section 6) can measurably improve initial bond quality, but add processing complexity and cost and, critically, their durability under realistic long-term alkaline exposure is not yet well characterized, which this review identifies as the highest-priority evidence gap.

The workability challenge at dosages above approximately 1.0% by volume (Section 7) is both a practical processing constraint and a quality-control risk: inadequately dispersed fiber produces zones of concentrated fiber separated by fiber-free concrete with non-uniform properties, a risk the two-stage mixing approach substantially mitigates without requiring a change in mix composition.

Absence of a standardized, universally reported dosage unit (Section 2) remains a structural weakness of the literature: studies variously report fiber content as weight percent of cement, volume percent of concrete, or mass per cubic metre, and this review has treated these as non-interchangeable rather than pooling them without conversion. A universal 0.5–1.0% optimum should not be presented as fixed, since the true optimum depends on fiber morphology, matrix composition, aspect ratio, mixing method and target performance; the upper end of the useful range for long macrofiber may be as low as 0.75% by volume, while short microfiber in self-compacting concrete with high superplasticizer dosage has been used at up to 1.25% without significant workability loss.

Additional gaps include: (i) limited systematic characterization of surface-modification durability under combined alkaline, thermal and freeze-thaw exposure, as opposed to as-treated initial bond strength; (ii) UV degradation of construction-grade PP fiber at or near the concrete surface, which is under-studied relative to the general polymer-ageing literature; (iii) absence of standardized design guidance connecting polymer-level variables (molecular weight, crystallinity, surface treatment) to composite-level design parameters, leaving practitioners without a coherent specification framework; (iv) inconsistent methodology across studies (fiber content reporting basis, concrete grade, curing age, aggregate specification), which the discussion below (Section 13) revisits in relation to the need for standardized testing; and (v) limited quantification of microplastic release from demolition and recycling of PP-FRC elements.

Table 9. Challenge-impact severity assessment for PP fiber-reinforced concrete.

Challenge	Mechanistic explanation	Severity (1–5, qualitative)	Proposed mitigation	Reference
Fiber–matrix bond degradation	Hydrophobic PP surface creates weak ITZ; bond strength decreases under sustained loading, thermal cycling and alkali exposure	4/5	Surface fibrillation; nano-silica sol-gel coating; plasma surface treatment	[16]
Workability reduction and balling	Increased surface area and fiber–fiber friction raises yield stress; fiber clumps resist uniform dispersion during mixing	5/5 (>1% vol.)	Two-stage mixing approach; PCE superplasticizers; optimized aggregate grading	[13, 21]
Compressive strength trade-off	PP fiber does not improve compressive strength proportionally; excess fiber introduces voids that reduce density and load capacity	3/5	Limit dosage to <1.0% vol.; combined with SCMs to fill voids	[55]
Freeze–thaw durability concerns	Water in microcracks near PP fiber expands during freezing; if bridging force is insufficient, microcracks propagate to macrocracks	4/5	Air-entraining admixtures; optimized fiber dosage; hybrid PP+steel systems	[16, 36]
Long-term ageing and interfacial stability	Gradual degradation of fiber–matrix bond under alkaline pore solution; UV exposure accelerates chain scission in exposed elements	4/5	Shielded embedment; hybrid systems; field monitoring programs	[35]
Surface–treatment durability data gap	Most surface-modification studies report as-treated bond improvement without long-term alkaline exposure testing	4/5	Standardized long-term alkaline immersion pull-out protocol	[6, 14]
Environmental and sustainability concerns	PP is fossil-fuel derived; non-biodegradable; production releases greenhouse gases; end-of-life disposal and microplastic release are problematic	3/5	Recycled PP fiber from industrial waste; volume-basis LCA for project justification	[41, 43, 54]
Dosage standardization deficit	Absence of universal design guidelines and consistent dosage-reporting basis across studies	4/5	Development of performance-based design codes; standardized volume-fraction reporting	[43]

Note: Severity scores are the authors' qualitative assessment (1 = low, 5 = severe) based on the frequency and consistency with which each challenge is reported as significant across the reviewed dataset; they are not derived from a standardized instrument and should be read as a synthesis judgement rather than a measured quantity (Table 9).

DISCUSSION

Three themes emerge from the evidence synthesized above. First, the consensus optimum PP fiber content of approximately 0.5–1.0% by volume is grounded in competing physical mechanisms rather than convention: below approximately 0.5% by volume, fiber spacing and total surface area are insufficient to bridge the matrix effectively; above approximately 1.0% by volume, adverse rheological effects (rising viscosity, yield stress and balling risk) outweigh further mechanical gains for most mix designs. This range shifts with aspect ratio, superplasticizer dosage and mixing method, and should be treated as mechanistically grounded rather than fixed.

Second, the performance hierarchy across mechanical properties, with flexural and tensile improvements consistently exceeding compressive-strength gains, follows directly from the crack-bridging mechanism established in Section 5.1 and has a direct design implication: PP fiber should be specified as secondary reinforcement for crack control and post-cracking ductility, not as primary load-bearing reinforcement substituting for steel rebar. This position is consistent with EN 14889-2, which permits macro-PP fiber to contribute to the static equilibrium of concrete elements without treating it as a replacement for conventional reinforcement in heavily loaded members.

Third, methodological inconsistency across the reviewed studies (Table 10), in dosage-reporting basis, concrete grade, testing age, curing conditions and aggregate specification, limits the extent to which a single quantitative structure-property relationship can be extracted from the pooled literature, and is a more fundamental limitation of the evidence base than any single mechanistic uncertainty. Standardized testing protocols (comparable in spirit to ASTM C1399 for residual strength of fiber-reinforced concrete) and a common, volume-fraction-based dosage-reporting convention, as adopted throughout this review, would substantially improve the comparability of future experimental results and their translation into design codes.

Table 10. Summary of methodological differences across the reviewed dataset and their influence on reported results.

Methodological variable	Range observed in reviewed dataset	Representative examples	Effect on comparability of reported results
Dosage-reporting basis	Volume fraction (%), weight % of cement or binder, kg/m ³ ; denominator frequently unstated	Screening dataset, Section 2 (55 studies)	Values are not directly comparable without a stated conversion basis; this review adopts volume fraction and kg/m ³ throughout (Section 2).
Concrete/mix grade	M20 to M45 and higher-strength mixes; conventional vibrated concrete and self-compacting concrete	Tables 4 and 7 sources	Baseline strength and workability differ substantially by grade, so percentage gains from fiber addition are not transferable across studies without normalizing to the control mix.
Curing conditions	Standard water curing, acidic-water curing, accelerated or elevated-temperature curing regimes	Section 8 compressive-strength sources	Curing medium and duration shifts absolute strength values independent of any fiber effect, confounding cross-study comparison of reported gains.
Testing age	7, 14, 28, 56 and 92 days, reported inconsistently across studies	Section 8, Table 7 sources	Early-age versus later-age testing changes the apparent magnitude of fiber-related strength and durability gains.
Test method / specimen geometry	Cube versus cylinder compressive testing; single- and double-fiber, fragmentation and dynamic pull-out protocols	Section 5 interfacial-testing sources	Absolute strength and interfacial shear strength values are method- and geometry-dependent and are not always directly comparable across the dataset.

FUTURE RESEARCH DIRECTIONS

Four priorities dominate the research agenda arising from this review. First, and most urgently, the long-term behavior of PP fiber under sustained alkaline exposure requires systematic investigation at

realistic exposure durations and pore-solution concentrations, since almost all currently reported bond and treatment-durability data reflect only as-treated or short-term conditions. Second, combined environmental ageing, alkaline exposure coupled with freeze–thaw cycling, thermal cycling and UV exposure acting concurrently rather than in isolation, should be prioritized over single-mechanism ageing studies, because in-service PP-FRC elements experience these stressors simultaneously and current single-variable testing likely underestimates cumulative degradation. Third, surface-treatment durability specifically, rather than as-treated bond improvement alone, is identified in Section 6 and Table 2 as the single largest gap between demonstrated laboratory performance and in-service reliability for plasma, corona, silane and mineral-coating strategies. Standardized long-term alkaline-immersion pull-out protocols, comparable in rigor to existing short-term pull-out standards, are needed before these treatments can be specified with confidence. Fourth, standardized testing and design guidelines, a common volume-fraction-based dosage-reporting convention (Section 2, Table 10), harmonized curing and testing-age protocols, and design guidance connecting polymer-level variables (molecular weight, crystallinity, surface treatment) to composite-level design parameters, are needed to translate the mechanistic evidence assembled in this review into codified practice. Beyond these four priorities, hybrid fiber systems combining PP with steel, basalt or natural fiber merit continued investigation for synergistic crack-resistance and toughness gains, the integration of PP fiber with 3D-printed concrete and structural health-monitoring systems represents an emerging application area and full-scale field trials remain necessary to validate laboratory-derived dosage, mixing and placement guidance under construction conditions.

CONCLUSIONS

This review has synthesized evidence from 55 primary sources on polypropylene fiber-reinforced cementitious composites, with a focus on the polymer structure, processing history, surface chemistry and fiber–matrix interface that govern composite-level performance. Polypropylene fiber performance cannot be reduced to a single dosage parameter: molecular weight, crystallinity and drawing ratio set the fiber’s intrinsic mechanical ceiling; surface energy and wettability, both inherently low for untreated PP, govern the achievable interfacial bond; and only once these polymer-level variables are accounted for does dosage determine composite-level outcomes. PP fibers consistently and substantially improve tensile, flexural and post-cracking toughness properties, most effectively at dosages of approximately 0.5–1.0% by fiber volume fraction, while compressive-strength effects are smaller and can reverse at higher dosage. Surface modification, particularly plasma treatment, silane coupling, maleic-anhydride grafting and alkaline or mineral-coating treatments, offers a credible route to improving the weak native PP-cement bond, but the durability of these treatments under sustained alkaline service conditions remains insufficiently characterized and is the priority evidence gap identified by this review. PP fiber’s non-corroding nature and volume-basis life-cycle profile broadly comparable to alternative fiber types support its continued use in crack-control and durability-enhancement roles, particularly in pavements, industrial flooring, precast elements and tunnel linings, provided dosage is reported and specified on a consistent, volume-fraction basis and PP fiber is positioned as secondary reinforcement rather than as a substitute for primary structural steel reinforcement.

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