

Mechanical Performance of OPC-53 Based Engineered Cementitious Composite (ECC): Split Tensile Strength and Flexural Strength Evaluation with Varied Fiber Reinforcement

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ABSTRACT

This paper presents a focused experimental investigation into the mechanical performance of Ordinary Portland Cement (OPC Grade 53) based Engineered Cementitious Composite (ECC) matrices reinforced with three fiber configurations: hooked-end steel fibers, Recron 3S polyester micro-fibers, and a hybrid combination of both. Coarse aggregates were entirely eliminated to conform to ECC micromechanical design principles, ensuring uniform fiber dispersion and strain-hardening capacity. Cylindrical and beam specimens were cast and cured for 7 and 28 days before being subjected to split tensile strength [IS 516 (Part-2):1999] and flexural strength [IS 516 (Part-1):2021] tests. Among all OPC mixes, the 0.8% steel fiber formulation achieved the highest split tensile strength of 5.75 MPa at 28 days — a 91% improvement over normal concrete — while the 2.4% steel fiber mix delivered the peak flexural strength of 18.50 MPa at 28 days. Excessive fiber dosages (2.4%) for Recron 3S induced fiber balling and workability loss, reducing 28-day strength values. The hybrid (1% Steel + 1% Recron 3S) configuration provided a balanced multi-scale crack-bridging mechanism, achieving 4.33 MPa split tensile and 9.66 MPa flexural strength at 28 days, though synergistic performance was constrained by workability limitations.

Keywords: Engineered Cementitious Composite (ECC); OPC-53; Split Tensile Strength; Flexural Strength; Steel Fiber; Recron 3S Fiber; Hybrid Fiber Reinforcement; Crack Bridging

1. Introduction

Conventional concrete is inherently brittle, exhibiting high compressive strength but poor tensile and flexural capacity. Fiber reinforced concrete (FRC) and, more recently, Engineered Cementitious Composites (ECC) have emerged as superior alternatives capable of delivering pseudo-strain hardening behavior through multiple micro-crack formation rather than single catastrophic cracking. ECC, conceived by Prof. Victor Li at the University of Michigan, is characterized by tensile strain capacities exceeding 3%, making it 50 times more flexible than ordinary concrete.

Central to ECC design is the elimination of coarse aggregates, which ensures matrix homogeneity and facilitates unhindered fiber bridging. The present work evaluates the Phase 1 OPC-based ECC system using three reinforcement strategies — hooked-end steel fibers, Recron 3S polyester fibers, and a hybrid combination — at volume fractions of 0.8%, 2.4%, and 1%+1%, respectively. The study focuses specifically on split tensile and flexural strength as the primary mechanical performance indicators relevant to real-world tensile and bending failures.

2. Literature Review

Al Kareem & Ahmed, (2021) In the paper titled "*Impact Resistance of Bendable Concrete Reinforced with Grids and Containing PVA Solution*," Al Kareem and Ahmed (2021) explored an eco-friendly composite blending Ordinary Portland Cement, Portland Limestone Cement (PLC), sand, structural steel mesh grids, polypropylene fibers, and a PVA chemical solution modifier. Mechanical testing at curing ages of 28, 56, and 90 days demonstrated a progressive compressive strength development, peaking at a 52.4% increase by day 90 compared to initial benchmarks. The results indicated that the dual-action reinforcement mechanism combining macro-scale grid reinforcement with micro-scale fibers yields excellent impact energy absorption capacity. The study concluded that utilizing PLC alongside structural mesh effectively transforms brittle concrete into a highly flexible, metal-like ductile material capable of restricting structural crack widths below a critical 100 mm threshold.

Khan et al., (2022) In their paper titled *"Effects of Various Mineral Admixtures and Fibrillated Polypropylene Fibers on the Properties of Engineered Cementitious Composite (ECC) Based Mortars,"* Khan et al. (2022) evaluated a sustainable matrix consisting of Ordinary Portland Cement, Fly Ash, Wheat Husk Ash (WHA), Rice Husk Ash (RHA), Glass Powder, quartz sand, and fibrillated polypropylene (PP) fibers. Evaluating specimens over curing periods of up to 90 days (and extending to 180 days for environmental exposure), the authors found that the optimized RHA mix achieved a peak compressive strength of 56 MPa at 90 days and a flexural strength of 6.5 MPa. The results, supported by microstructural XRD, FTIR, SEM, and EDX analysis, indicated that combining agro-industrial wastes with low-cost PP fibers optimizes mechanical packing and microcrack bridging. The study concluded that this multi-waste hybrid approach offers an eco-friendly alternative with exceptional chemical durability, suffering only a 1.07% compressive strength loss after a 180-day immersion in a sodium sulfate solution.

Sridhar (2022) conducted a study titled *"Durability study on engineered cementitious composites with hybrid fibers under sulfate and chloride environments"* utilizing cement, Fly Ash with cenospheres, Polyvinyl Alcohol (PVA) fibers, and high-stiffness steel fibers. Following targeted long-term curing and environmental immersion intervals, the study assessed compressive, flexural, and uni-axial tensile strengths to mitigate brittle fractures. The results revealed that an optimized hybrid blend of 1.5% PVA fibers and 0.5% steel fibers delivered superior mechanical performance and exceptional degradation resistance compared to single-fiber mixes. The paper concluded that this tailored micromechanical fiber synchronization successfully controls both the initiation and propagation of cracks, effectively preventing the internal penetration of aggressive chemical ions under simultaneous sulfate and chloride attacks typical of marine environments.

Sudhikumar et al. (2022) presented *"An Experimental Study on Bendable Concrete Using Recron 3s Fibre,"* focusing on an M25 structural concrete grade combined with fine/coarse aggregates and domestic, triangular cross-section Recron 3s polyester fibers. Specimens underwent standardized water immersion curing for 7, 14, and 28 days before mechanical failure testing. The results demonstrated that an exact critical fiber addition of 0.5% optimized performance, achieving a 12.45% increase in split tensile strength and a 65.33% boost in flexural strength at 28 days, whereas higher fiber contents caused workability issues that degraded strength. The authors concluded that uniform dispersion of these cost-effective polyester fibers prevents plastic and drying shrinkage crack propagation, successfully transforming standard M25 concrete into a highly homogenous, ultra-ductile composite with a strain capacity exceeding 3%.

Subiksha M. et al. (2023), in their state-of-the-art review paper *"Engineered Cementitious Composite (ECC) – A State Art Review,"* evaluated a highly ductile concrete matrix composed of OPC 53 cement, fine aggregate, fly ash (up to 30–40% replacement), silica fume, superplasticizers, and reduced or eliminated coarse aggregate. Utilizing diverse fiber variants (such as PVA, Recron 3S, polypropylene, nylon, and steel) at an optimal 2% content alongside water–cement ratios of 0.40–0.55, the reviewed literature examined specimens via compressive, split tensile, flexural, workability, SEM, and three-point bending tests. The results demonstrated that fiber addition—particularly Recron 3S and PVA—profoundly improved ductility, crack control, self-healing behavior, and flexural strength, achieving an exceptional tensile strain capacity of 3–7%. The study concluded that ECC offers superior flexibility, durability, and sustainability over conventional concrete, making it ideal for seismic zones, bridge decks, and repair works, while highlighting future research pathways in hybrid fiber systems, geopolymers eco-binders, and large-scale structural configurations.

3. Problem statement

- **Workability Limitations:** High volume fractions or excessive dosages (e.g., 2.4%) of high-surface-area synthetic fibers like Recron 3S cause severe "fiber balling," trap air pockets, exhaust available cement paste, and degrade mechanical strength.
- **Consolidation Difficulties:** High macro-fiber content (such as steel fibers) creates fresh-state consolidation and compaction challenges.
- **Synergy Penalties:** Combining different fibers into a hybrid system can introduce fresh-state flowability issues that completely override the theoretical bridging benefits of a multi-scale crack arrest mechanism.

4. Research objective

- Completely eliminating coarse aggregates to conform to micromechanical design principles and ensure uniform fiber dispersion.
- Investigating and comparing three distinct fiber reinforcement strategies: hooked-end steel macro-fibers, Recron 3S polyester micro-fibers, and a hybrid combination of both.
- Evaluating these strategies at precise volume fractions (0.8%, 2.4%, and 1%+1% hybrid) over standard curing periods of 7 and 28 days to determine the optimal dosages and thresholds.

5. Significance of the study

- **Optimization of Ductile Structural Elements:** The findings pinpoint optimal fiber thresholds (e.g., 0.8% steel fiber for peak split tensile strength at 5.75 MPa, and 2.4% steel fiber for peak flexural strength at 18.50 MPa), which provides direct reference data for engineering structural materials that resist tensile and bending failures.
- **Understanding Multi-Scale Failure Mechanisms:** It highlights how different fiber scales interact with the matrix; rigid steel fibers act as macro-bridges across split failure planes, while massive numerical densities of lightweight Recron 3S micro-fibers intercept early plastic shrinkage cracks.
- **Practical Workability Warning Limits:** The study offers critical real-world limitations for concrete design mixes, proving that excessive dosages (2.4%) of synthetic micro-fibers induce an inversion of performance due to balling and compaction inefficiencies.
- **Foundation for Future Hybrid Composites:** By exposing the flowability and porosity penalties of a 1%+1% hybrid configuration, the paper opens up a pathway to refine superplasticizer dosages and explore asymmetric hybrid ratios (e.g., 1.5% Steel + 0.5% Recron) to successfully unlock true multi-scale crack-bridging synergy

6. Materials and Mix Design

2.1 Binder — OPC Grade 53

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was employed as the primary binding material. The cement contributes to Calcium Silicate Hydrate (C–S–H) gel formation, which provides the fundamental strength of the matrix. Key physical properties include: specific gravity 3.15, standard consistency 30–32%, initial setting time 30 minutes, and final setting time 12 hours.

2.2 Fine Aggregate

River sand conforming to IS 383:2016 and passing through a 4.75 mm sieve was used. The sand belonged to Zone-II with a specific gravity of 2.6 and water absorption of 1.35%. Coarse aggregate was entirely excluded to preserve ECC ductility principles.

2.3 Fiber Reinforcement

Three fiber types were investigated: (i) Recron 3S polyester synthetic micro-fibers (6 mm length, 20 μ m diameter, tensile strength 400–600 MPa, elastic modulus 8–12 GPa) used for ductility and crack control; (ii) hooked-end steel macro-fibers (30 mm length, 0.75 mm diameter, aspect ratio 40, tensile strength 1000–2000 MPa, elastic modulus 200 GPa) used for high tensile capacity and load transfer; and (iii) a hybrid combination of both for multi-scale crack arrest. Volume fractions tested were 0.8% and 2.4% for individual fibers, and 1%+1% for the hybrid.

2.4 Superplasticizer

Polycarboxylate ether (PCE) based superplasticizer conforming to IS 9103:1999 was added at 1% by weight of binder to maintain workability at low water-binder ratios and prevent fiber balling.

3. Experimental Methodology

3.1 Split Tensile Strength Test

Split tensile strength tests were conducted on cylindrical specimens (150 mm diameter $\times$ 300 mm length) were cast and cured for 7 and 28 days. Each specimen was placed horizontally in a Compression Testing Machine (CTM), and a compressive line load was applied along the longitudinal axis until failure. The split tensile strength (f_t) was calculated from the failure load.



Fig.1 Split tensile testing

3.2 Flexural Strength Test

Flexural strength tests were conducted on beam specimens (100 mm $\times$ 100 mm $\times$ 500 mm) were cast and cured for 7 and 28 days. Each beam was tested under a standard three-point or four-point bending setup. Crack initiation, propagation, and failure mode were recorded. The modulus of rupture was computed from the peak load.



Fig. 2 Flexural testing

4. Results and Discussion — Split Tensile Strength

4.1 Tabulated Results

Table 1 presents the individual and average split tensile strength values at 7 and 28 days for all OPC-based mixes. Each average is computed from three replicate specimens (M1, M2 and M3).

Table 1: Split Tensile Strength Results — OPC Grade 53 [IS 516 (Part-2):1999]

Mix Type	SP (%)	Fiber (%)	7D M1	7D M2	7D M3	7D Avg	28D M1	28D M2	28D M3	28D Avg
Normal Concrete	0	0	1.55	1.55	1.69	1.59	3.39	2.54	3.11	3.01
Steel Fiber (0.8%)	1	0.8	4.38	3.81	3.53	3.90	5.80	5.80	5.65	5.75
Steel Fiber (2.4%)	1	2.4	3.25	1.69	2.54	2.49	5.80	5.09	5.37	5.42
Recron 3S (0.8%)	1	0.8	2.82	2.97	2.54	2.77	2.82	3.81	3.53	3.38
Recron 3S (2.4%)	1	2.4	2.12	1.98	2.26	1.52	2.97	3.25	3.04	3.09
Hybrid (Steel+Recron 1+1%)	1	1+1	2.97	2.54	2.68	2.73	4.95	3.81	4.24	4.33

4.2 Analysis and Discussion

Normal (unreinforced) concrete recorded baseline split tensile strengths of 1.59 MPa and 3.01 MPa at 7 and 28 days respectively, confirming its well-documented brittleness under tensile loading. The introduction of fibers consistently improved performance across all mixes at 28 days.

4.2.1 Steel Fiber Mixes

The 0.8% steel fiber mix demonstrated outstanding performance — 3.90 MPa at 7 days and 5.75 MPa at 28 days — representing a 91% improvement over the unreinforced control at 28 days. This superior outcome stems from the high elastic modulus (200 GPa) of the hooked-end steel fibers, which act as rigid macro-bridges across the split failure plane, arresting crack propagation and transforming catastrophic brittle failure into a progressive, ductile mechanism.

The 2.4% steel fiber mix yielded a lower 7-day average of 2.49 MPa due to fiber balling and compaction difficulties at higher dosages. By 28 days, however, continued cement hydration densified the interfacial transition zone (ITZ), improving fiber anchorage and raising strength to 5.42 MPa. Despite this recovery, the 2.4% mix remained slightly below the 0.8% optimum, confirming that excessive steel fiber content — even with 1% superplasticizer — compromises fresh-state consolidation.

4.2.2 Recron 3S Fiber Mixes

At 0.8% dosage, Recron 3S fibers improved 7-day split tensile strength to 2.77 MPa and 28-day strength to 3.38 MPa. These lightweight polyester micro-fibers are highly effective at intercepting early plastic shrinkage micro-cracks throughout the matrix volume due to their massive numerical density per unit volume. However, raising the Recron 3S content to 2.4% produced a drastic reduction in 7-day strength to just 1.52 MPa — lower than unreinforced concrete — caused by the enormous specific surface area of the synthetic fibers exhausting available cement paste and inducing severe fiber balling and air entrapment. The 28-day recovery to 3.09 MPa highlights partial matrix self-repair through continued hydration, but the strength remained near-equivalent to normal concrete.

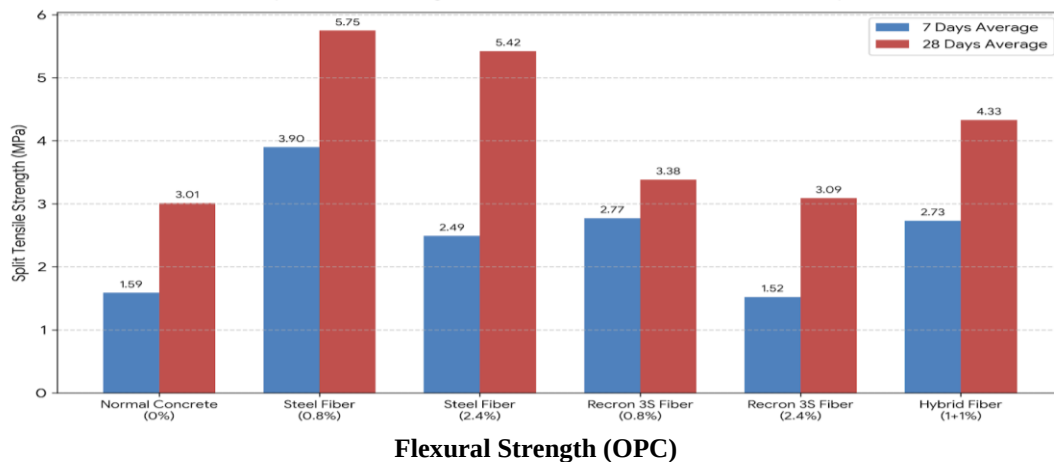
4.2.3 Hybrid Fiber Mix (1% Steel + 1% Recron 3S)

The hybrid combination achieved 2.73 MPa at 7 days and 4.33 MPa at 28 days. This multi-scale crack arrest mechanism — where fine Recron fibers intercept micro-cracks while steel fibers bridge macro-cracks under peak stress — provides a 44% enhancement over normal concrete at 28 days. The performance was constrained relative to the 0.8% steel-only mix due to the interaction between the combined 2.0% total fiber volume and available superplasticizer, which limited fresh-state flowability and fiber distribution uniformity.

4.3 Comparative Performance Summary — Split Tensile Strength

Figure 1 (below) summarizes the 28-day split tensile strength of all OPC mixes. The chart clearly indicates the superiority of the 0.8% steel fiber mix and the threshold effect where 2.4% Recron 3S performs comparably to plain concrete.

Figure 1: 28-Day Split Tensile Strength Comparison — OPC Mixes (MPa)



5.1 Tabulated Results

Table 2 presents the individual specimen and average flexural strength values at 7 and 28 days for all OPC-based mixes.

Table 2: Flexural Strength Results — OPC Grade 53 [IS 516 (Part-1):2021]

Mix Type	SP (%)	Fiber (%)	7D M1	7D M2	7D M3	7D Avg	28D M1	28D M2	28D M3	28D Avg
Normal Concrete	0	0	7.00	10.00	8.50	8.50	7.50	11.00	9.50	9.33
Steel Fiber (0.8%)	1	0.8	6.00	8.00	9.00	7.66	14.50	14.50	13.50	14.16
Steel Fiber (2.4%)	1	2.4	10.00	11.50	13.00	11.50	17.00	20.00	18.50	18.50
Recron 3S (0.8%)	1	0.8	10.50	10.00	9.50	10.00	12.50	12.50	11.50	12.16
Recron 3S (2.4%)	1	2.4	7.00	8.00	6.50	7.16	13.00	9.00	11.00	11.00
Hybrid (Steel+Recron 1+1%)	1	1+1	6.00	6.50	7.50	6.66	10.50	9.00	9.50	9.66

5.2 Analysis and Discussion

5.2.1 Steel Fiber Mixes

Steel fibers emerged as the most effective reinforcement for flexural resistance. The bottom tension face of a bending beam is where macro-cracks preferentially propagate, and hooked-end steel fibers act as internal micro-bridges precisely across this zone. The 2.4% steel fiber mix achieved the highest overall performance — rising from 11.50 MPa at 7 days to 18.50 MPa at 28 days — representing a 98.3% improvement over unreinforced concrete. Even at a lower dosage of 0.8%, steel fibers produced a remarkable 85% strength gain between 7 and 28 days (from 7.66 to 14.16 MPa), confirming that as the matrix cures and bonds tightly around the hooked anchors, load transfer becomes highly efficient.

5.2.2 Recron 3S Fiber Mixes

Recron 3S fibers exhibited a distinct optimal threshold for flexural performance. At 0.8% dosage, they outperformed steel fibers at the 7-day mark (10.00 MPa vs. 7.66 MPa), attributable to the massive numerical density of micro-fibers effectively controlling early plastic shrinkage cracking across the beam's tension zone. However, increasing the dosage to 2.4% reduced 28-day flexural strength from 12.16 MPa to 11.00 MPa. This decline reflects the high specific surface area of fine synthetic filaments choking the matrix, inducing fiber balling, trapping air pockets, and drastically reducing compaction efficiency — phenomena well-documented in fiber-reinforced composites.

5.2.3 Hybrid Fiber Mix (1% Steel + 1% Recron 3S)

The hybrid mix recorded the lowest flexural strength among fiber-reinforced mixes, with 6.66 MPa at 7 days and 9.66 MPa at 28 days — only marginally better than normal concrete at 28 days. While hybrid configurations theoretically leverage synthetic fibers for micro-crack arrest and steel fibers for macro-crack bridging, the combined 2.0% total fiber volume imposed a workability penalty that exceeded what 1% PCE superplasticizer could compensate. The resulting poor consolidation and elevated porosity in the tensile zone completely overrode the theoretical bridging advantage. Future studies should explore asymmetric hybrid ratios (e.g., 1.5% Steel + 0.5% Recron) or increased HRWRA dosage to unlock the synergistic potential.

5.3 Comparative Performance Summary — Flexural Strength

Figure 2 summarizes the 7-day and 28-day flexural strengths of all OPC mixes. The progressive strength gain from 7 to 28 days across all mixes, driven by continued C–S–H gel formation around fiber anchorage zones, is clearly evident.

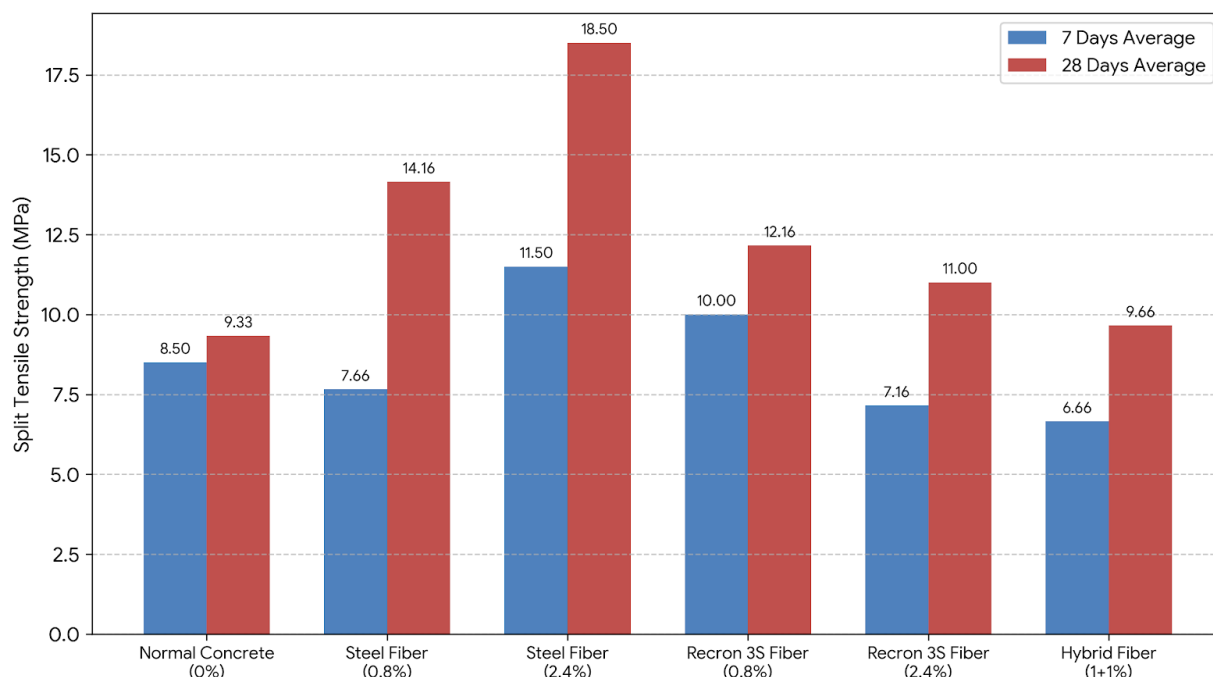


Figure 2: 7-Day vs. 28-Day Flexural Strength Comparison — OPC Mixes (MPa)

6. Consolidated OPC Mechanical Performance Summary

Table 3 consolidates the average split tensile and flexural strength values at both curing ages for all OPC mix variants, providing a direct reference for inter-mix comparison.

Table 3: Consolidated Mechanical Performance Summary — OPC ECC Mixes

Mix Type	7D Split Tensile (MPa)	28D Split Tensile (MPa)	7D Flexural (MPa)	28D Flexural (MPa)
Normal Concrete	1.59	3.01	8.50	9.33
Steel Fiber 0.8%	3.90	5.75	7.66	14.16
Steel Fiber 2.4%	2.49	5.42	11.50	18.50
Recron 3S 0.8%	2.77	3.38	10.00	12.16
Recron 3S 2.4%	1.52	3.09	7.16	11.00
Hybrid (1%+1%)	2.73	4.33	6.66	9.66

7. Conclusion

Based on the experimental investigation of OPC Grade 53 based ECC with varied fiber reinforcement, the following key conclusions are drawn:

1. Steel fiber reinforcement is the most effective enhancer of both split tensile and flexural strength in OPC-based ECC, with 0.8% being optimal for split tensile strength (5.75 MPa, 28-day) and 2.4% being optimal for flexural strength (18.50 MPa, 28-day).
2. Recron 3S fiber is effective at low dosages (0.8%), achieving 3.38 MPa split tensile and 12.16 MPa flexural at 28 days, but exhibits a balling-induced performance inversion at 2.4% dosage.
3. The hybrid (1% Steel + 1% Recron 3S) configuration provides balanced multi-scale crack control (28-day split tensile: 4.33 MPa; flexural: 9.66 MPa) but requires refined superplasticizer dosage to realise its full synergistic potential.
4. Progressive cement hydration from 7 to 28 days consistently densifies the interfacial transition zone (ITZ) around fibers, stabilising inter-specimen scatter and improving overall structural reliability.

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