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Mechanical Properties of Concrete Reinforced with Hybrid BFRP Minibars and Micro Fibers: Experimental Study and Evaluation

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ABSTRACT: Corrosion of steel fibers and limited understanding of hybrid reinforcement mechanisms hinder the application of fiber-reinforced concrete in aggressive environments. This study presents a combined experimental and analytical investigation into the mechanical performance of a novel multi-scale hybrid fiber-reinforced concrete incorporating corrosion-resistant basalt fiber-reinforced polymer (BFRP) minibars alongside various micro fibers. A comprehensive experimental program, including compression and splitting tensile tests on multiple hybrid combinations, was conducted to systematically evaluate the effects of fiber type, volume fraction, and elastic modulus. Analytically, a modified hybrid reinforcement index model was developed and correlated with mechanical properties, revealing that a quadratic function provides a more accurate fit than traditional linear models. Furthermore, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was applied for a multi-criteria performance evaluation integrating mechanical and economic indicators. Results demonstrate that compressive and splitting tensile strengths are increased from 51.87 to 68.48 MPa and from 3.18 to 4.73 MPa, by 32.0% and 48.7%, respectively, with the optimum mixture containing 0.75% micro steel fibers and 1.25% BFRP minibars. The reinforcement index was found to have an optimal range of 0.3–0.5 for maximizing performance. The findings highlight the innovation of using a modified reinforcement index coupled with TOPSIS-based multi-objective assessment, offering a reliable framework for the design of durable and high-performance fiber-reinforced concrete for long-life infrastructure applications.

KEYWORDS: BFRP minibar; fiber reinforced concrete; hybrid reinforcement; reinforcing index; TOPSIS evaluation

1 Introduction

Fiber-reinforced concrete (FRC) is a composite material that has been widely adopted in civil engineering applications. The incorporation of fibers into the cementitious matrix generates a three-dimensional randomly distributed network, which optimizes the internal microstructure, alleviates stress concentrations, and suppresses the initiation and propagation of microcracks through fiber bridging mechanisms. This reinforcing effect facilitates tensile load transfer across cracked sections and enhances the mechanical properties of the otherwise brittle matrix [1–3]. Given that damage in concrete occurs at multiple length scales, hybrid fiber systems have been developed to provide toughening across different dimensional levels [4].

Hybrid fiber-reinforced concrete (HFRC) integrates two or more fiber types to attain superior strength and toughness [5]. Fibers are conventionally categorized by diameter into microfibers (<0.3 mm) and macrofibers (>0.3 mm) [6,7]. Microfibers primarily enhance pre-cracking behavior by retarding the formation and propagation of microcracks through stress dispersion and interfacial bonding [8–10]. Macrofibers, typically incorporated at volume fractions exceeding 1.0% [11], improve post-cracking performance by bridging macroscopic cracks, thereby increasing load-carrying capacity and toughness [12–15]. Their random spatial distribution establishes a three-dimensional network that transfers stresses across fractured surfaces [8,12–15]. Consequently, the hybrid application of micro- and macrofibers enables synergistic crack control across scales, leading to concurrent improvements in both mechanical properties and durability [16].

Steel fibers are recognized as one of the most effective reinforcements for enhancing the strength and toughness of concrete [17]. Previous studies have shown that the combination of hooked-end macro steel fibers with micro steel fibers can improve tensile performance [18], and hybrid steel fiber systems have demonstrated enhanced static mechanical properties and workability [19,20]. Nevertheless, the flexural and tensile behavior of steel FRC is highly sensitive to fiber orientation [18,20–23]. Moreover, in aggressive environments, the bond between steel fibers and the cementitious matrix is susceptible to degradation, which compromises mechanical performance [24–26]. In response to these durability concerns, synthetic fiber-based HFRC has attracted increasing attention owing to its inherent corrosion resistance and crack-inhibiting capability, attributes derived from its chemical stability and the bridging effect of fibers across cracks [27,28]. For instance, hybrid combinations of polyolefin (PO) and polypropylene (PP) fibers have been reported to enhance both compressive and splitting tensile strengths [29]. Conversely, the synergistic effect of steel and PP fibers on strength may be limited [30], and the incorporation of steel fibers with PVA fibers has been observed to occasionally reduce compressive strength [31,32].

Basalt fiber provides high strength and corrosion resistance [33,34]. Macro basalt fiber (also named as “BFRP Minibar”), a needle-shaped composite of continuous fibers in resin, offers lightweight, high-strength, and durable reinforcement [35–37]. Hybridizing macro and micro basalt fibers yields synergistic improvements in mechanical properties and impact resistance [37,38], with micro fibers enhancing microcrack resistance alongside BFRP Minibar [38,39]. Although several studies have explored the use of BFRP minibars in combination with other fibers for concrete reinforcement [35–39], the influence of such hybrid systems on the fundamental mechanical properties of concrete remains insufficiently systematic. The reported effects vary considerably depending on fiber type, geometry, and dosage, and the underlying mechanisms governing the hybridization of BFRP minibars with various micro fibers have yet to be fully elucidated. Moreover, different mechanical properties—such as compressive strength, splitting tensile strength, and flexural performance—exhibit distinct and sometimes conflicting responses to fiber incorporation, complicating the selection of an optimal mixture design. In practical engineering applications, there is a notable absence of a unified evaluation framework that simultaneously accounts for both fundamental mechanical performance and economic cost, making it difficult to achieve a scientifically sound and balanced design that reconciles structural performance with financial viability.

To address these gaps, the present study systematically investigates the effects of fiber type, elastic modulus, and volume fraction on the compressive and splitting tensile behavior of multi-scale hybrid fiber-reinforced concrete incorporating BFRP minibars and various micro fibers. A comprehensive experimental program is conducted to characterize the fundamental mechanical properties of a wide range of hybrid mixtures. Analytically, a modified hybrid reinforcement index model is developed and correlated with mechanical performance, enabling improved prediction of strength enhancement. Furthermore, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method, integrated with a combined weighting approach, is employed to perform a multi-criteria performance evaluation that incorporates both

mechanical indicators and material cost, offering a holistic assessment framework. The primary novelty and contribution of this study lie in: (i) establishing a systematic experimental database for BFRP minibar-based hybrid fiber-reinforced concrete; (ii) proposing a quadratic reinforcement index model that provides more accurate predictions than conventional linear formulations; and (iii) introducing an integrated evaluation methodology that supports the balanced optimization of mechanical performance and economic efficiency, thereby providing a practical reference for the design of durable, cost-effective fiber-reinforced concrete for infrastructure applications.

2 Methodology

2.1 Raw Materials

2.1.1 Concrete

The concrete mixture was prepared using 42.5-grade ordinary Portland cement, medium-sized river sand as fine aggregate, and crushed basalt stone (5–15 mm) as coarse aggregate. All materials were sourced from local suppliers in Jiangsu Province, China, and tap water was used for mixing. The mix design followed JGJ 55-2011 [40] for C40-grade concrete, with proportions per cubic meter of 469 kg cement, 629 kg fine aggregate, 1071 kg coarse aggregate, and 230 kg water. The measured 28-day cube compressive strength of the plain concrete was 51.87 MPa.

2.1.2 Fibers

Eight types of fibers were used in this study, including four macro fibers—hooked-end steel fibers, straight polypropylene and polyvinyl alcohol fibers, and twisted BFRP minibars—and four micro fibers: micro steel, polypropylene, polyvinyl alcohol, and chopped basalt fibers. The selection of fiber types was based on elastic modulus and dimensional characteristics to facilitate comparative analysis. Macro steel fibers featured hooked ends, macro polypropylene and polyvinyl alcohol fibers had embossed surfaces for improved bond, and BFRP minibars adopted a twisted geometry, which has been shown to provide superior performance in previous studies [35–37]. Detailed properties of all fibers are provided in Table 1.

Table 1: Properties of used fibers.

Size	Fiber		Length (mm)	Diameter (mm)	Density (g/cm ³)	Elastic Modulus (GPa)	Tensile Strength (MPa)
	ID	Type					
Micro fibers	pp	Micro PP fibers	9	0.017	0.9	3.5	500
	pva	Micro PVA fibers	8	0.04	1.3	41	1600
	b	Micro basalt fibers	9	0.013	2.65	85	2600
	s	Micro steel fibers	8	0.12	7.85	200	2500
Macro fibers	PP	Macro PP fibers	30	0.74	0.9	2.9	450
	PVA	Macro PVA fibers	30	0.65	1.3	23	900
	B	BFRP minibar	30	0.84	1.88	46	1311
	S	Macro steel fibers	30	0.97	7.85	200	1100

Note: The abbreviations pp, pva, b, and s denote micro polypropylene fibers, micro polyvinyl alcohol fibers, micro basalt fibers, and micro steel fibers, respectively. Conversely, PP, PVA, B, and S represent macro polypropylene fibers, macro polyvinyl alcohol fibers, BFRP minibar, and macro steel fibers, respectively. This consistent naming convention will be maintained throughout subsequent sections of this paper.

2.2 Mixture Design and Specimen Preparation

2.2.1 Mixture Design

The experimental design considered fiber volume fraction and hybrid configuration as the primary variables, with total fiber contents ranging from 0% to 2.0% by volume of concrete. Single-fiber reinforced concrete groups were designed as controls, as detailed in Table 2. In the first hybrid series, the micro fiber content was fixed at 0.5%, while the macro fiber content varied from 1.0% to 1.5%. In the second hybrid series, the macro fiber content was fixed at 1.25%, and the micro fiber content ranged from 0.25% to 0.75%.

Table 2: Fiber content design of concrete.

Test Groups	Micro Fibers		Macro Fibers		Total Volume Content/%
	Micro Fiber	Volume Content/%	Macro Fiber	Volume Content/%	
PC	–	–	–	–	0
S-pp0.5	pp	0.5			0.5
S-pva0.5	pva	0.5			0.5
S-b0.5	b	0.5			0.5
S-s0.5	s	0.5			0.5
S-PP1.25			PP	1.25	1.25
S-PVA1.25			PVA	1.25	1.25
S-B1.25			B	1.25	1.25
S-S1.25			S	1.25	1.25
H1-b0.5PP1.0			PP	1.0	
H1-b0.5PVA1.0			PVA	1.0	
H1-b0.5B1.0			B	1.0	1.5
H1-b0.5S1.0			S	1.0	
H1-b0.5PP1.25			PP	1.25	
H1-b0.5PVA1.25	b	0.5	PVA	1.25	1.75
H1-b0.5B1.25			B	1.25	
H1-b0.5S1.25			S	1.25	
H1-b0.5PP1.5			PP	1.5	
H1-b0.5PVA1.5			PVA	1.5	
H1-b0.5B1.5			B	1.5	2.0
H1-b0.5S1.5			S	1.5	
H2-pp0.25B1.25			pp	0.25	
H2-pva0.25B1.25			pva	0.25	1.5
H2-b0.25B1.25			b	0.25	
H2-s0.25B1.25			s	0.25	
H2-pp0.5B1.25			pp	0.5	
H2-pva0.5B1.25	B	1.25	pva	0.5	1.75
H2-b0.5B1.25			b	0.5	
H2-s0.5B1.25			s	0.5	
H2-pp0.75B1.25			pp	0.75	
H2-pva0.75B1.25			pva	0.75	2.0
H2-b0.75B1.25			b	0.75	
H2-s0.75B1.25			s	0.75	

2.2.2 Specimen Preparation

(1) Mixing

To minimize the negative effects of residual mud on concrete workability, coarse aggregates were rinsed with high-pressure water on a vibrating screen and then air-dried prior to mixing. The detailed mixing procedure is illustrated in Fig. 1.

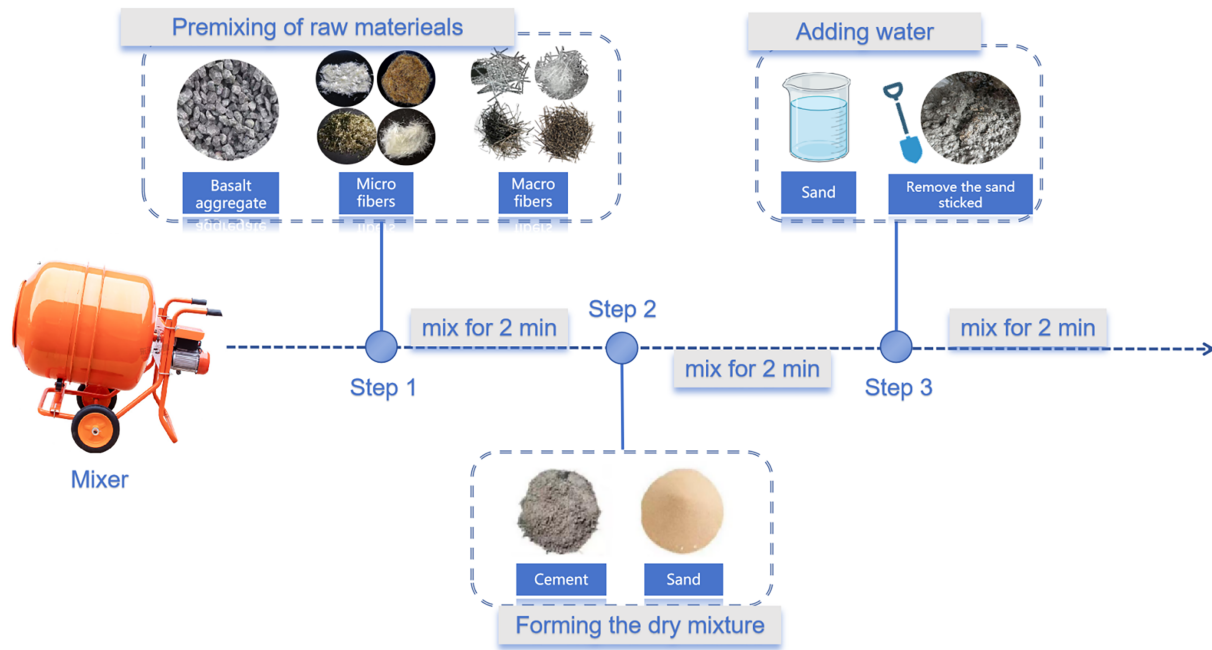


Figure 1: Mixing procedure.

(2) Casting

Freshly mixed concrete was poured into oil-coated molds. The molds were placed on a vibrating table and vibrated for 1–2 min to ensure proper compaction. Upon appearance of bleeding water on the surface, excess paste was removed and the surface was leveled with a trowel. A thin polyethylene film was then placed over the top surface to prevent moisture loss.

(3) Curing

Specimens were demolded 24 h after casting and subsequently cured in water at room temperature for 28 days. All specimen preparation and curing procedures followed GB/T 50081-2019 [41].

2.3 Test Method

Cubic compression tests were conducted in accordance with GB/T 50081-2019 [41] using a compression testing machine at a loading rate of 0.5 MPa/s. Splitting tensile tests were performed on a 100T hydraulic servo-controlled fatigue testing machine at a loading rate of 0.05 MPa/s. The test setups and loading configurations are shown in Fig. 2.

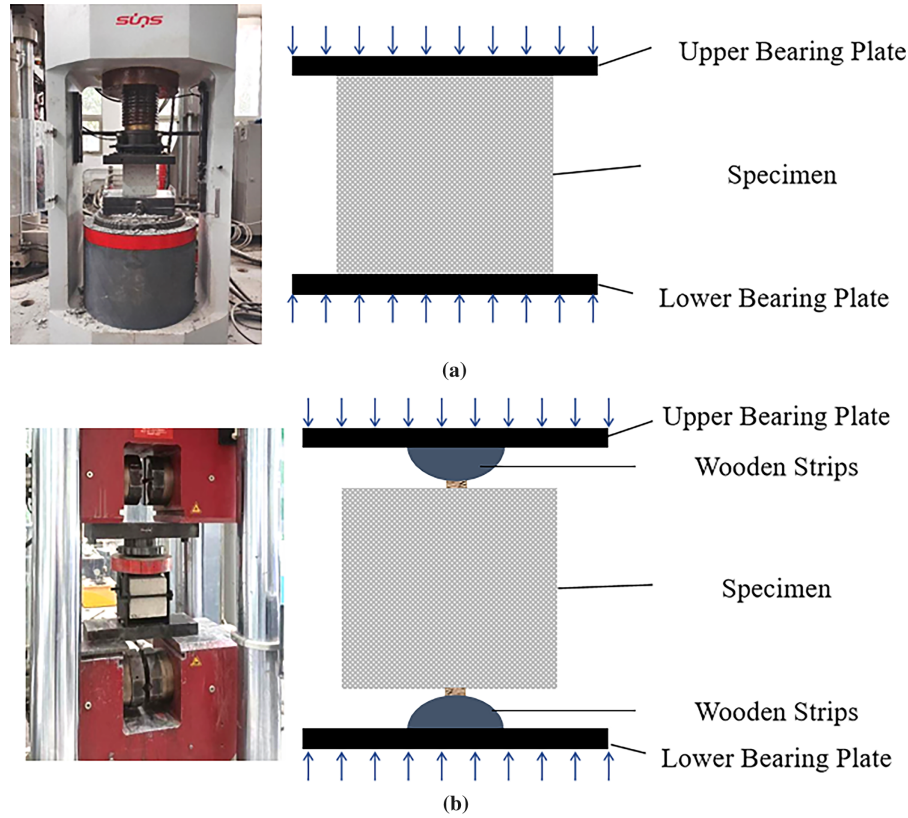


Figure 2: Test loading diagram: (a) compression test; (b) splitting tensile test.

For the compression test, the molding side surfaces of the cube specimens served as the loading faces. The loading faces and bearing plates were wiped clean, and the specimen was centered on the lower platen. After the testing machine was started and uniform contact was established between the specimen and the upper and lower bearing plates, continuous loading was applied until failure, and the test data were recorded. The compressive strength of each cube specimen was calculated using Eq. (1):

$$f_{cc} = \frac{F_c}{A_c} \quad (1)$$

where f_{cc} is the cubic compressive strength of concrete, F_c is the ultimate compressive load, A_c is the cross-section area of compressive specimen.

For the splitting tensile test, the loading surfaces were selected as the faces perpendicular to the top molding surface of the cube specimen. Curved bearing blocks and packing strips were placed between the loading platens and the specimen, with careful alignment of the centerlines to ensure uniform contact. The test machine was then started, and a continuous load was applied until failure. The splitting tensile strength was calculated using Eq. (2):

$$f_{ts} = \frac{2F}{\pi A} = 0.637 \frac{F_{ts}}{A_{ts}} \quad (2)$$

where f_{ts} is the splitting tensile strength of concrete, F_{ts} is the ultimate load in splitting tensile test, A_{ts} is the cross-section area of splitting tensile specimen. All tests were performed on three specimens per mixture, and the reported strengths are average values, in accordance with GB/T 50081-2019 [41]. It should be noted

that the proposed predictive model is calibrated based on standardized 100 mm cubic specimens, and its direct extrapolation to full-scale members would require additional consideration of size effects.

3 Results and Discussions

The results of mechanical tests are summarized in [Table 3](#).

Table 3: Results of mechanical tests.

Test Group	Compressive Strength			Splitting Tensile Strength		
	Strength (MPa)	COV	K	Strength (MPa)	COV	K
PC	51.87	4.15%	–	3.18	5.26%	–
S-pp0.5	48.48	5.10%	–6.5%	3.20	1.58%	+0.6%
S-pva0.5	52.77	2.78%	+1.7%	3.40	7.11%	+6.9%
S-b0.5	50.92	3.78%	–1.8%	3.28	8.07%	+3.1%
S-s0.5	58.59	4.21%	+13.0%	4.08	9.16%	+28.2%
S-PP1.25	51.34	3.02%	–1.0%	3.21	9.25%	+1.0%
S-PVA1.25	55.07	2.47%	+6.2%	3.74	3.29%	+17.6%
S-B1.25	56.36	8.04%	+8.7%	3.67	7.62%	+15.3%
S-S1.25	57.60	2.92%	+11.0%	3.78	5.04%	+18.9%
H1-b0.5PP1.0	49.18	1.79%	–5.2%	3.07	6.58%	–3.5%
H1-b0.5PVA1.0	49.74	5.40%	–4.1%	3.46	6.39%	+8.8%
H1-b0.5B1.0	52.83	2.83%	+1.9%	3.47	4.11%	+9.1%
H1-b0.5S1.0	55.20	2.10%	+6.4%	3.65	4.28%	+14.8%
H1-b0.5PP1.25	48.93	0.60%	–5.7%	3.10	4.83%	–2.5%
H1-b0.5PVA1.25	52.93	1.15%	+2.0%	3.65	2.82%	+14.8%
H1-b0.5B1.25	55.83	6.22%	+7.6%	3.79	10.16%	+19.2%
H1-b0.5S1.25	57.32	0.39%	+10.5%	3.82	5.04%	+20.1%
H1-b0.5PP1.5	48.62	2.24%	–6.3%	3.13	6.07%	–1.6%
H1-b0.5PVA1.5	50.77	1.05%	–2.1%	3.82	8.33%	+20.1%
H1-b0.5B1.5	57.28	3.34%	+10.4%	3.87	5.76%	+21.7%
H1-b0.5S1.5	58.94	1.05%	+13.6%	4.06	12.18%	+27.6%
H2-pp0.25B1.25	51.62	2.39%	–0.5%	3.99	7.88%	+25.4%
H2-pva0.25B1.25	53.35	1.46%	+2.9%	4.05	8.17%	+27.4%
H2-b0.25B1.25	54.07	2.49%	+4.2%	3.71	7.42%	+16.7%
H2-s0.25B1.25	60.26	3.14%	+16.2%	4.09	8.97%	+28.7%
H2-pp0.5B1.25	53.56	1.99%	+3.3%	3.96	6.14%	+24.5%
H2-pva0.5B1.25	55.25	0.76%	+6.5%	4.23	8.87%	+33.0%
H2-b0.5B1.25	55.83	5.95%	+7.6%	3.79	10.16%	+19.2%
H2-s0.5B1.25	66.77	2.89%	+28.7%	4.37	9.11%	+37.5%
H2-pp0.75B1.25	49.62	1.63%	–4.3%	3.92	5.92%	+23.2%
H2-pva0.75B1.25	57.18	2.87%	+10.2%	4.18	2.83%	+31.4%
H2-b0.75B1.25	59.75	3.24%	+15.2%	3.95	6.29%	+24.2%
H2-s0.75B1.25	68.48	2.63%	+32.0%	4.73	8.76%	+48.7%

Note: K denote the relative increase in strength of the experimental group compared to the control group.

3.1 Compressive Strength

Fig. 3 presents the influence of micro- and macro-fibers on compressive strength. With a constant 0.5% volume of micro basalt fibers, Fig. 3a indicates that compressive strength increases with the elastic modulus of the macro fiber. However, at a 1.5% macro fiber volume, low-modulus fibers such as PP and PVA result in reduced strength. Fig. 3b shows that increasing the volume fraction of BFRP minibars (B) or macro steel (S) fibers generally enhances compressive strength. Fig. 3c demonstrates that compressive strength generally increases with the elastic modulus of the micro fiber. As shown in Fig. 3d, incorporating micro fibers generally raises strength with increasing dosage.

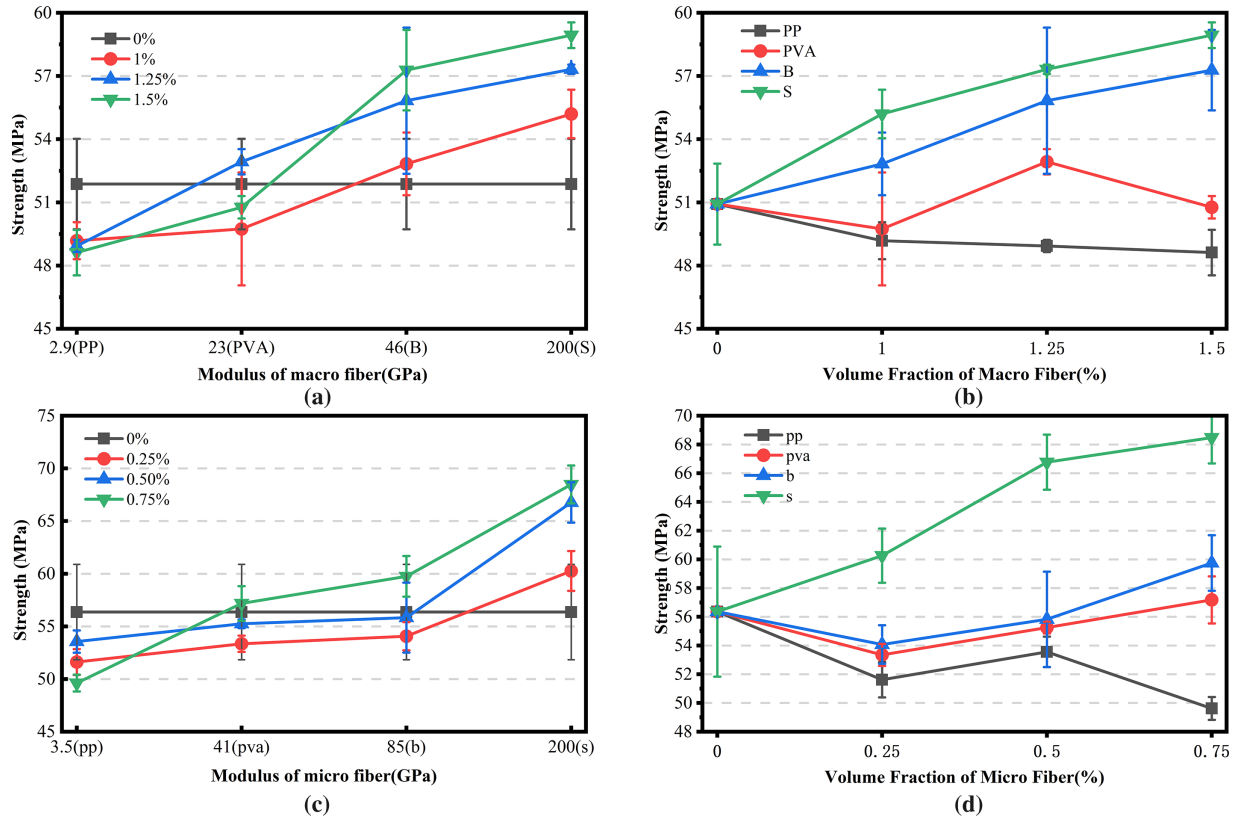


Figure 3: Effects of fiber on compressive strength: (a) modulus of macro fiber; (b) content of macro fiber; (c) modulus of micro fiber, and (d) content of micro fiber.

The observed trends are closely related to the distinct roles of different fiber types. The limited enhancement of macro PP fibers likely reflects their low elastic modulus and consequently weak crack-restraining capacity [16]. For macro PVA fibers, the strength reduction at higher dosages is likely associated with fiber agglomeration observed during mixing, leading to non-uniform dispersion. As shown in Fig. 4, macro fibers effectively bridge macroscopic cracks and improve post-cracking integrity, whereas micro basalt fibers are observed bridging microcracks within the matrix. These observations suggest that macro fibers, including BFRP minibars and steel fibers, primarily enhance post-cracking load-bearing capacity and toughness [8], while micro fibers contribute mainly to pre-cracking performance by restraining microcrack propagation. They are believed to fracture upon matrix cracking and contribute little to post-cracking resistance, consistent with the literature [24].

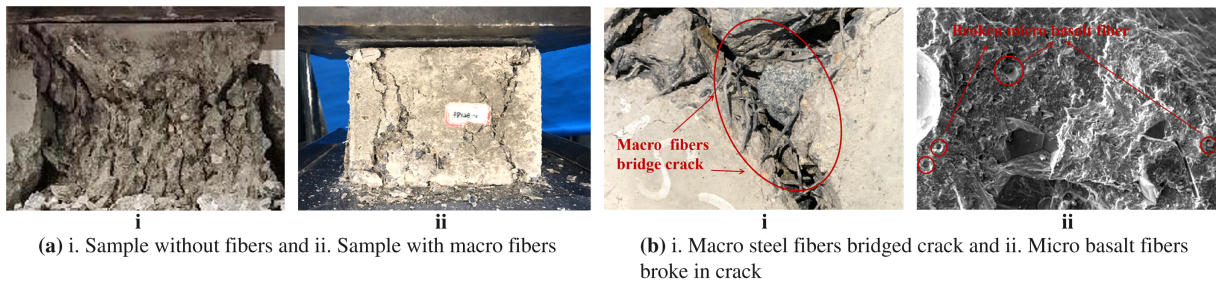


Figure 4: Samples and fibers morphology after loading: (a) samples and (b) fibers.

3.2 Splitting Tensile Strength

Fig. 5 presents the effects of micro- and macro-fibers on splitting tensile strength. As shown in Fig. 5a, splitting tensile strength generally increases with the elastic modulus of the macro fiber, with macro PP fibers showing the least improvement. Fig. 5b indicates that, except for macro PP fibers, splitting tensile strength improves with increasing volume fraction for the other three macro fiber types. In Fig. 5c, at a fixed BFRP minibar content of 1.25%, the addition of micro PVA and micro steel fibers substantially enhances splitting tensile strength. As shown in Fig. 5d, splitting tensile strength generally increases with higher micro fiber dosage for most fiber types, with the exception of micro PP fibers. The limited enhancement of micro PP fibers across all dosage levels is likely due to their low elastic modulus, which provides weak restraint against microcrack propagation.

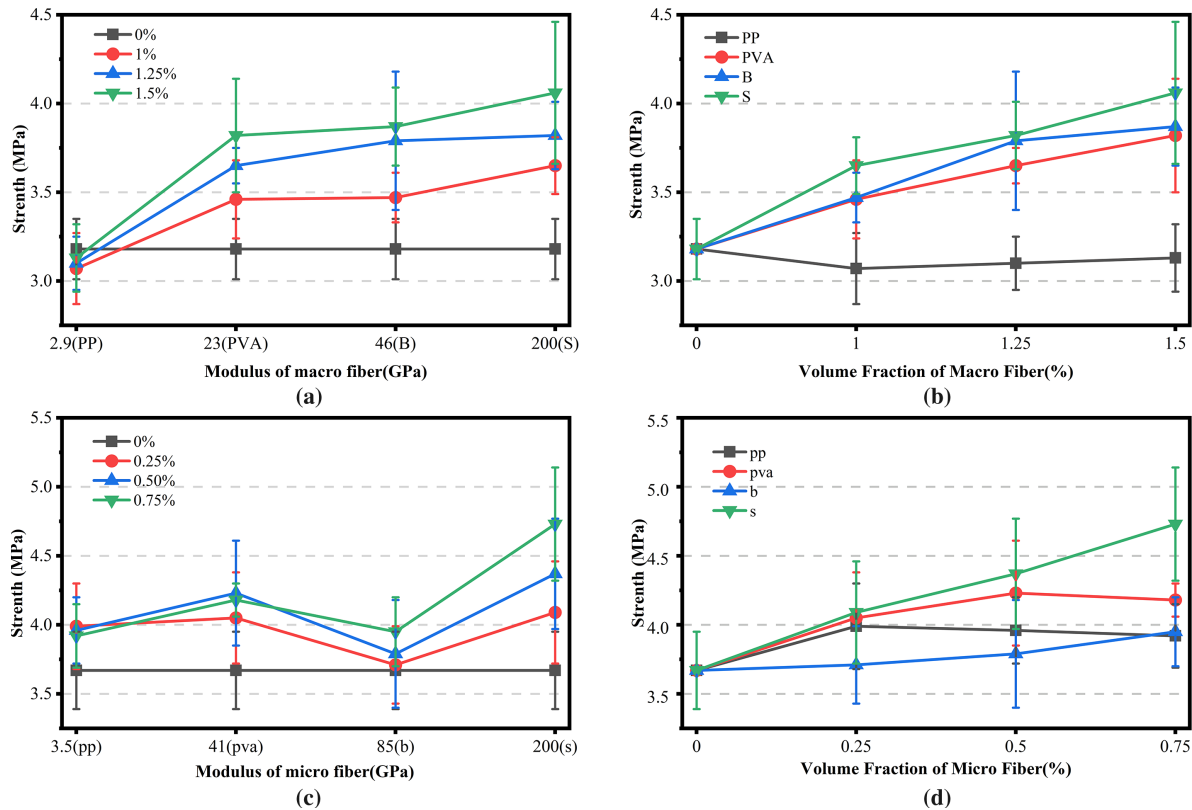


Figure 5: Effects of fiber on splitting tensile strength: (a) modulus of macro fiber; (b) content of macro fiber; (c) modulus of micro fiber, and (d) content of micro fiber.

3.3 Multiscale Hybrid Fiber-Reinforced Concrete Mechanical Property Fitting and Prediction

The mechanical properties of FRC are influenced by multiple factors. For fiber, key factors include geometric shape, volume fraction, and elastic modulus. The Reinforcing Index (RI), shown in Eq. (3), is used to characterize fiber properties [42].

$$RI = W_f \frac{l}{d} \quad (3)$$

where W_f represents the fiber weight fraction; l indicates the fiber length; d indicates the fiber diameter.

The original formulation in Eq. (3), however, applies only to steel fiber-reinforced concrete with a single fiber type, and is therefore inadequate for evaluating the influence of other fiber types or hybrid combinations on concrete mechanical properties. In response, numerous studies have established empirical relationships between the hybrid fiber reinforcing index and the mechanical performance of concrete, generally showing a positive correlation. A summary of these existing fitting relationships is presented in Table 4 [42–47].

Table 4: Fitting relationships between RI of fibers and mechanical performance of concrete.

References	Fibers	Reinforcing Index	Properties	Fitting Function	Correlation Coefficient
Ezeldin and Balaguru [42]	Macro steel fiber	$RI = w_f \frac{l}{d}$	Compressive strength	$f = f_0 + 3.51RI$	0.75
			Modulus	$E = E_0 + 31051RI$	0.75
			Compressive toughness ratio	$TR = TR_0 + 0.075RI$	0.65
Nataraja et al. [43]	Macro steel fiber	$RI = w_f \frac{l}{d}$	Compressive strength	$f = f_0 + 2.1604RI$	0.76
			Peak strain	$\varepsilon = \varepsilon_0 + 0.0006RI$	0.94
			Compressive toughness ratio	$TR = TR_0 + 0.0978RI$	0.85
Said and Razak [44]	Micro PE fiber	$RI = w_f \frac{l}{d}$	Compressive strength	$f = -0.0143RI + 55.959$	0.98
			First crack load in bending	$f = -0.001RI + 1.6617$	0.89
			Peak load in bending	$f = 0.0012RI + 0.9325$	0.84
Abadel et al. [45]	Macro steel fiber and macro pp fiber	$RI_v = \sum_i^n RI_{vi}$ $RI_{vi} = v_i \frac{k_i l_i}{d_i} \frac{E_i}{E_s}$	Compressive strength	$f = f_0 + 5.222RI_v$	0.27
			Splitting tensile strength	$f = f_0 + 2.9203RI_v$	0.88
			Modulus	$f = f_0 + 6.496RI_v$	0.89
			Toughness index	$TI = -0.22RI_v^2 + 0.47RI_v + 1$	0.70
Almusallam et al. [46]	Macro steel fiber and macro pp fiber	$RI_v = \sum_i^n RI_{vi}$ $RI_{vi} = v_i \frac{k_i l_i}{d_i} \left(\frac{f_{ti}}{f_{ts}}\right)^\alpha$	Fracture energy	$G_f = 4.4RI_v + 4.3$	0.80
			Flexural strength	$f = f_0 + 9.44RI_v$	0.82
			Residual flexural strength	$f = 18.6RI_v - 0.05$	0.71

(Continued)

Table 4 (continued)

References	Fibers	Reinforcing Index	Properties	Fitting Function	Correlation Coefficient
Cao and Li [47]	Macro steel fiber and macro pva fiber	$RI_v = \sum_i^n RI_{vi}$ $RI_{vi} = v_i \frac{k_i l_i}{d_i} \left(\frac{f_{ti}}{f_{ts}} \right)^\alpha$	Compressive strength	$f = f_0(-26.42RI_v^2 + 13.11RI_v + 1)$	0.38
			Compressive toughness	$T = T_0(-121.24RI_v^2 + 53.87RI_v + 1)$	0.70
			Flexural strength	$f = f_0(-22.48RI_v^2 + 9.86RI_v + 1)$	0.79

To overcome this limitation, Abadel et al. [45] introduced a modified formulation for the reinforcing index that accounts for fiber volume fraction, aspect ratio, elastic modulus, and anchorage performance. The resulting hybrid fiber reinforcing index is expressed in Eqs. (4) and (5), which yielded improved fitting accuracy.

$$RI_v = \sum_i^n RI_{vi} \quad (4)$$

$$RI_{vi} = v_i \frac{k_i l_i}{d_i} \frac{E_i}{E_s} \quad (5)$$

where RI_v represents the hybrid fiber reinforcing index, calculated as the sum of the individual reinforcing indices (RI_{vi}) for each fiber type. The index for a given fiber (i) accounts for its volume fraction (v_i), bond factor (k_i), length (l_i), diameter (d_i), and the ratio of its elastic modulus (E_i) to that of steel (E_s). Based on the statistical analysis of prior test data [42,48], k_i is assigned as 0.5 for micro steel fibers and 0.1 for other micro fibers, while for macro fibers it is taken as 1.0 for steel and 0.8 for other macro fiber types. The RI of experimental groups based on Eqs. (4) and (5) is presented in Table 5.

Table 5: Calculated value of RI .

Group	Micro Fiber			Macro Fiber			Reinforcing Index ($RI_1 + RI_2$)
	$V/\%$	l/d	RI_1	$V/\%$	l/d	RI_2	
H1-b0.5PP1.0	0.5	692	0.147	1.0	41	0.005	0.152
H1-b0.5PVA1.0	0.5	692	0.147	1.0	46	0.042	0.190
H1-b0.5B1.0	0.5	692	0.147	1.0	36	0.099	0.246
H1-b0.5S1.0	0.5	692	0.147	1.0	31	0.309	0.456
H1-b0.5PP1.25	0.5	692	0.147	1.25	41	0.006	0.153
H1-b0.5PVA1.25	0.5	692	0.147	1.25	46	0.053	0.200
H1-b0.5B1.25	0.5	692	0.147	1.25	36	0.123	0.270
H1-b0.5S1.25	0.5	692	0.147	1.25	31	0.387	0.534
H1-b0.5PP1.5	0.5	692	0.147	1.5	41	0.007	0.154
H1-b0.5PVA1.5	0.5	692	0.147	1.5	46	0.064	0.211
H1-b0.5B1.5	0.5	692	0.147	1.5	36	0.148	0.295
H1-b0.5S1.5	0.5	692	0.147	1.5	31	0.464	0.611
H2-pp0.25B1.25	0.25	529	0.002	1.25	36	0.123	0.126

(Continued)

Table 5 (continued)

Group	Micro Fiber			Macro Fiber			Reinforcing Index ($RI_1 + RI_2$)
	$V/\%$	l/d	RI_1	$V/\%$	l/d	RI_2	
H2-pva0.25B1.25	0.25	200	0.010	1.25	36	0.123	0.133
H2-b0.25B1.25	0.25	692	0.074	1.25	36	0.123	0.197
H2-s0.25B1.25	0.25	67	0.083	1.25	36	0.123	0.207
H2-pp0.5B1.25	0.5	529	0.005	1.25	36	0.123	0.128
H2-pva0.5B1.25	0.5	200	0.021	1.25	36	0.123	0.144
H2-b0.5B1.25	0.5	692	0.147	1.25	36	0.123	0.270
H2-s0.5B1.25	0.5	67	0.167	1.25	36	0.123	0.290
H2-pp0.75B1.25	0.75	529	0.007	1.25	36	0.123	0.130
H2-pva0.75B1.25	0.75	200	0.031	1.25	36	0.123	0.154
H2-b0.75B1.25	0.75	692	0.221	1.25	36	0.123	0.344
H2-s0.75B1.25	0.75	67	0.250	1.25	36	0.123	0.373

The fitting baseline functions can be broadly categorized into two forms, as shown in Eqs. (6) and (7).

$$f = f_0(A_1 RI + A_2) \quad (6)$$

$$f = f_0(B_1 RI^2 + B_2 RI + B_3) \quad (7)$$

where f represents the mechanical property indicator of multiscale hybrid fiber-reinforced concrete; f_0 represents the mechanical property indicator of plain concrete; A_1 and A_2 are the undetermined coefficients of the linear fitting function; B_1 , B_2 and B_3 are the undetermined coefficients of the quadratic fitting function.

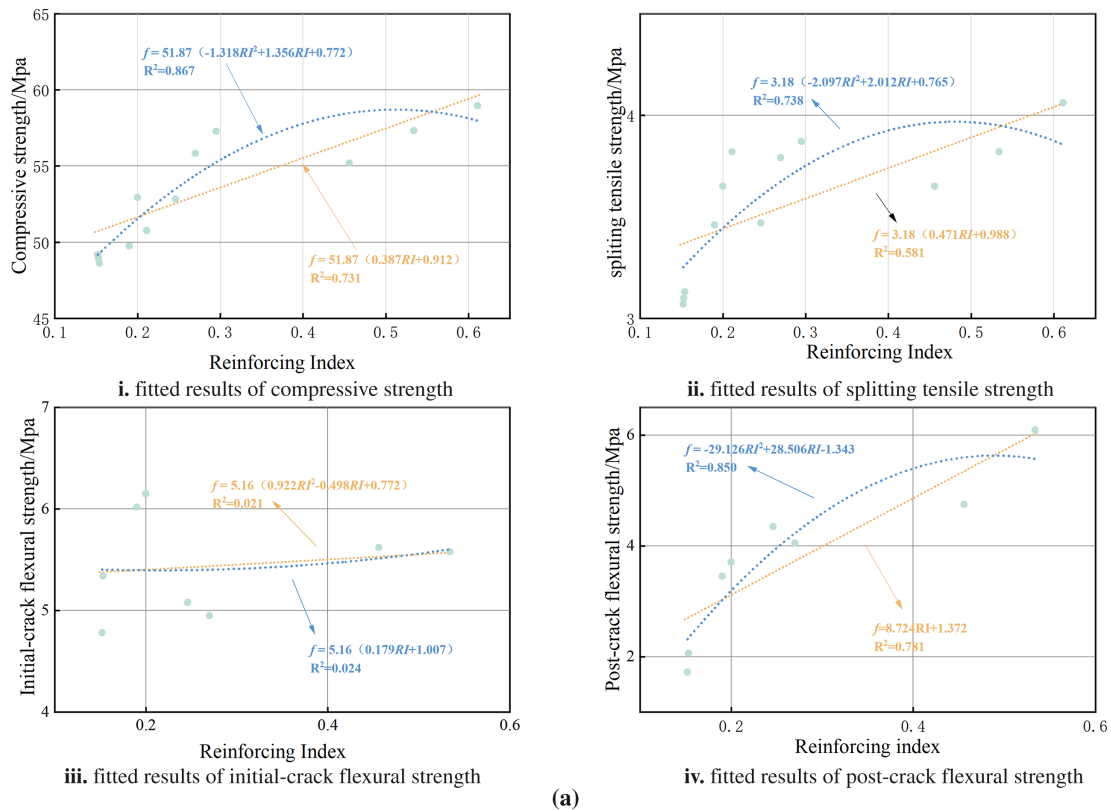
Both baseline functions were used to fit the experimental data. The performance indicators included in the fitting were compressive strength and splitting tensile strength from the present study, as well as initial-crack flexural strength and post-crack flexural strength reported in Ref. [8]. This comprehensive analysis was intended to establish predictive relationships for the mechanical properties of multi-scale hybrid fiber-reinforced concrete, thereby providing a basis for future research and practical applications. The fitted results for both linear and quadratic functions are summarized in Table 6 and plotted in Fig. 6.

The quadratic model outperforms the linear form for compressive and splitting tensile strengths, yielding R^2 values up to 0.867 and 0.709, respectively. For flexural responses, however, both models exhibit poor correlations ($R^2 \leq 0.218$), indicating that the current RI formulation inadequately captures the mechanisms governing flexural behavior. This is because initial cracking strength is governed largely by fiber volume fraction rather than the composite effects of geometry, modulus, and bond quality that RI purports to reflect, while microfibers fracture upon matrix cracking and offer negligible post-cracking resistance. Nevertheless, a model that reliably predicts two fundamental mechanical properties—compressive and splitting tensile strengths—remains useful when its limitations are clearly acknowledged.

Table 6: Fitted results of linear and quadratic function.

Model	Reinforcing Index	Mechanical Performance	f_0	Undetermined Coefficients			R^2
				A_1 or B_1	A_2 or B_2	B_3	
Linear function	Test group 1	Compressive strength	51.87	0.387	0.912	–	0.731
		Splitting tensile strength	3.18	0.471	0.988	–	0.581
		Initial-crack flexural strength	5.16	0.179	1.007	–	0.024
		Post-crack flexural strength	–	8.724	1.372	–	0.781
	Test group 2	Compressive strength	51.87	0.975	0.944	–	0.683
		Splitting tensile strength	3.18	0.416	1.197	–	0.586
		Initial-crack flexural strength	5.16	0.562	0.924	–	0.172
		Post-crack flexural strength	–	–5.590	6.723	–	0.176
Quadratic function	Test group 1	Compressive strength	51.87	–1.318	1.356	0.772	0.867
		Splitting tensile strength	3.18	–2.097	2.012	0.765	0.738
		Initial-crack flexural strength	5.16	0.922	–0.498	0.772	0.021
		Post-crack flexural strength	–	–29.126	28.506	–1.343	0.850
	Test group 2	Compressive strength	51.87	0.180	0.889	0.912	0.689
		Splitting tensile strength	3.18	9.320	–4.152	1.671	0.709
		Initial-crack flexural strength	5.16	–1.116	1.018	0.882	0.173
		Post-crack flexural strength	–	65.280	–32.200	9.172	0.218

Note: Due to the negligible post-crack flexural strength of plain concrete specimens, the linear baseline function for the relationship between the RI of hybrid fiber and the post-crack peak strength has been adjusted to $f = A_1RI + A_2$, and the corresponding quadratic baseline function has been modified to $f = B_1RI^2 + B_2RI + B_3$.

**Figure 6:** (Continued)

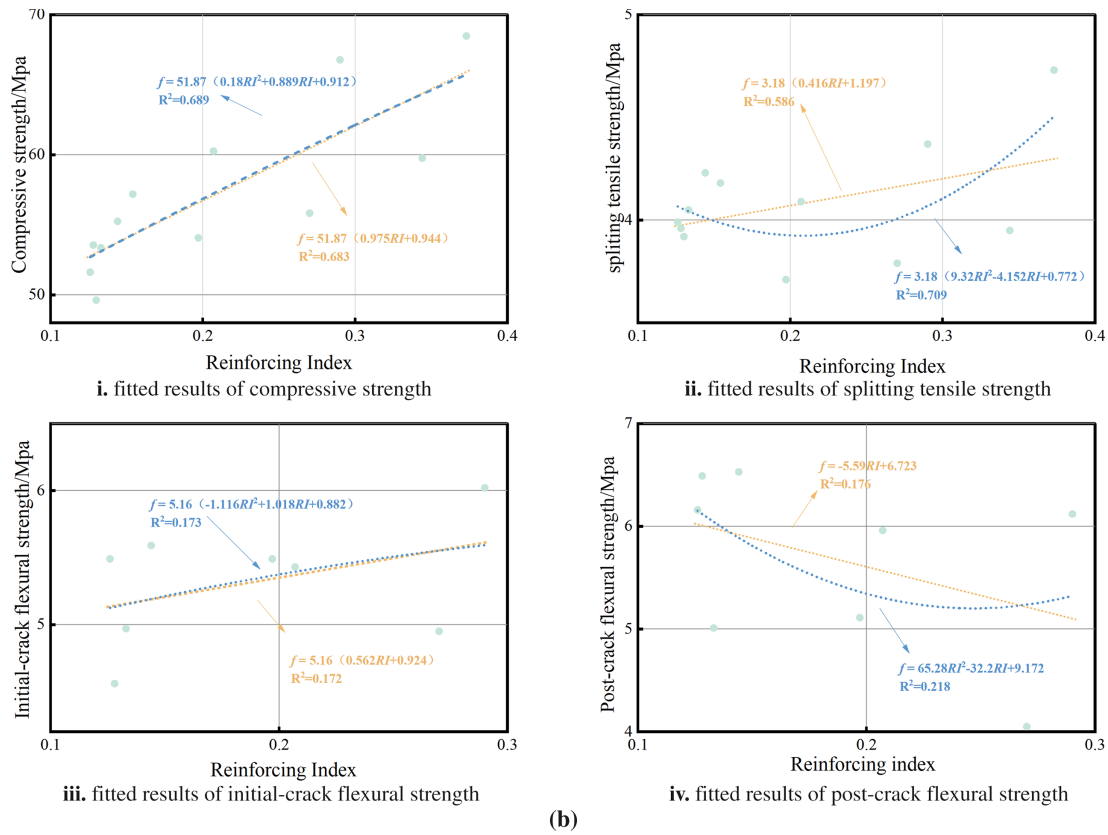


Figure 6: Fitted results: (a) group 1 and (b) group 2.

To assess the accuracy and applicability of the proposed quadratic fitting function, validation was performed through both model comparison and external literature data. Compared with existing fitting models [45,49], the proposed model demonstrates superior correlation with experimental data ($R^2 = 0.867$ vs. 0.735, shown as Fig. 7a), confirming the advantage of a quadratic function over linear forms as also noted by Khan [49]. External validation against independent studies [50–52] further confirms the model's predictive capability, with R^2 values of 0.801 and 0.742 for compressive and splitting tensile strength, respectively, demonstrating its applicability to multi-scale hybrid fiber-reinforced concrete combining macro and micro fibers, shown as Fig. 7b. It should be acknowledged, however, that given the finite number of data points per mixture group, the risk of overfitting cannot be entirely excluded; the external validation nonetheless suggests that the improved fit reflects a genuine trend rather than an artifact of overfitting.

It is worth noting that the experimental results and fitted model are derived from standard specimen dimensions. While size effects may influence the absolute values when applying the model to large-scale structures, the relative performance trends and the optimal RI range identified remain valid. For practical engineering design, the established fitting equations enable designers to predict strength from a given fiber combination or to back-calculate the required RI for a target performance level. The proposed model should therefore be applied within its validated scope—namely, for predicting compressive and splitting tensile strengths of multi-scale hybrid fiber-reinforced concrete—rather than generalized to flexural responses, where the RI formulation exhibits weak correlation.

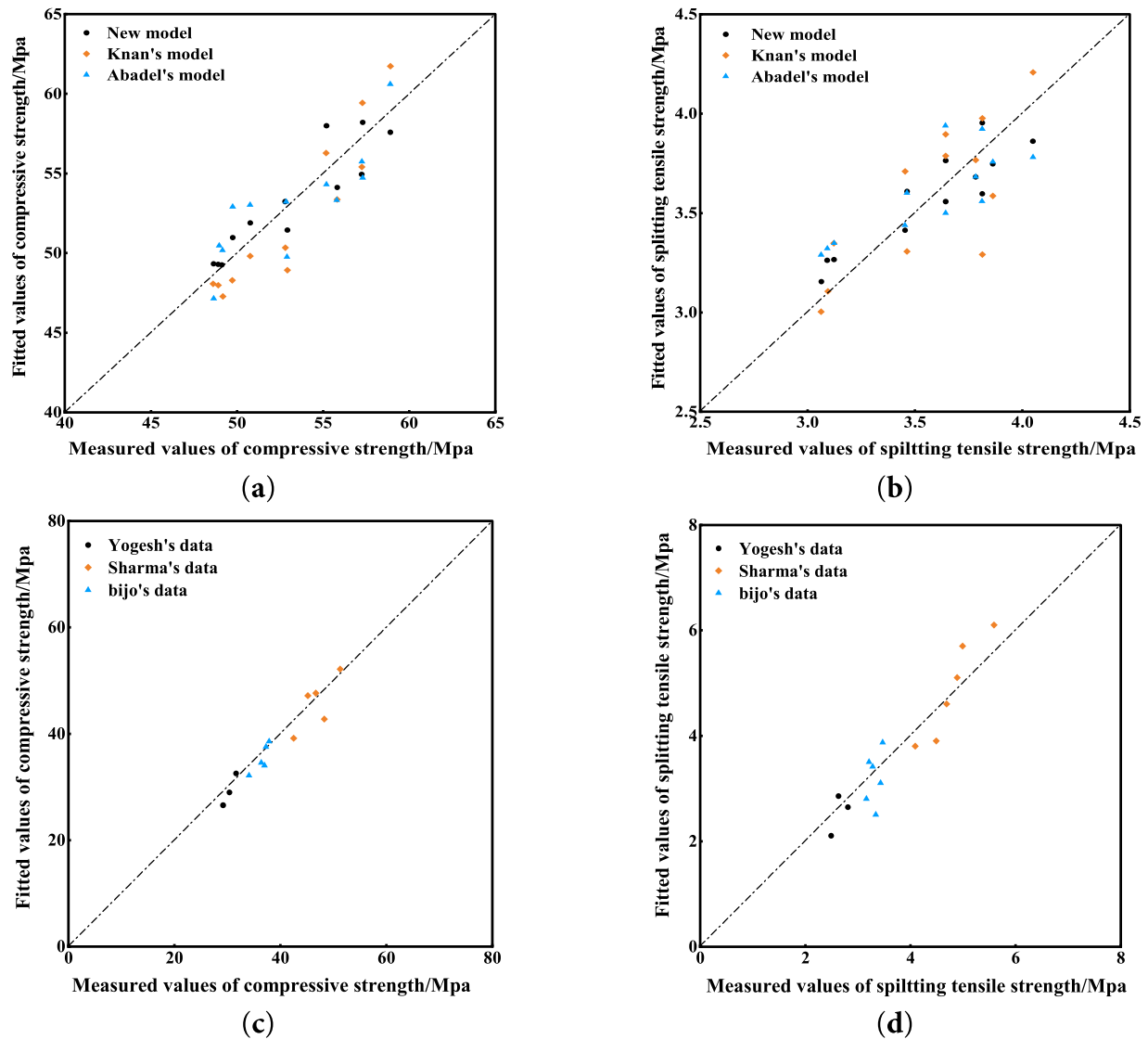


Figure 7: Fitted results based on the proposed models: (a) compressive strength fitted with existing models; (b) splitting tensile strength fitted with existing models; (c) compressive strength fitted with the proposed models; (d) splitting tensile strength fitted with the proposed models.

3.4 Performance Evaluation of FRC Based on the TOPSIS Method

To incorporate both subjective judgment and objective information, this study adopts a combined weighting approach that integrates the Analytic Hierarchy Process (AHP) and the entropy weight method. The subjective weights derived from AHP are denoted as α , and the objective weights obtained from the entropy method for the j -th indicator as β . Their synthesis yields the composite weights σ . The TOPSIS method is then applied based on the normalized weighted decision matrix, from which the positive and negative ideal solutions are identified, and each alternative is evaluated by its relative closeness to these solutions.

Given the varied application scenarios and engineering requirements for concrete, a comprehensive assessment balancing mechanical performance and economy is necessary. Among the full set of mixtures designed and tested in this study, the majority are systematic parameter-variation sequences, such as varying macro fiber content from 1.0% to 1.5% at a fixed micro fiber dosage, intended to capture trends in

mechanical behavior rather than to serve as independent candidate designs. For the TOPSIS evaluation, twelve representative groups are selected to ensure diversity and avoid redundancy. The plain concrete and single-fiber reinforced groups are included as baselines. Within each parameter sequence, only representative intermediate or optimal dosage levels are retained, as adjacent formulations differ only marginally and contribute little additional information to the ranking. The best-performing combinations from different fiber types and modulus levels are also incorporated to cover a broad design space. This selection ensures a balanced and non-redundant comparison without biasing the relative ranking. Among the five evaluation indicators listed in Table 7, compressive strength (K_1) and splitting tensile strength (K_2) are experimental data obtained from the present study. The flexural indicators—initial cracking strength (K_3) and equivalent residual flexural strength (K_4)—are adopted from the authors' previous work [8], in which the identical mixture proportions, fiber types, dosages, and curing conditions were used, ensuring a one-to-one correspondence with the mixtures tested herein. The cost indicator (K_5) is calculated from fiber unit price and density.

Table 7: Initial data for comprehensive evaluation indicators.

Groups	Mechanical Properties				Economic Perspectives
	K_1 (MPa)	K_2 (MPa)	K_3 (MPa) [8]	K_4 (MPa) [8]	K_5 (¥/m ³) ¹
PC	51.87	3.18	5.16	0.00	0
b0.5	50.92	3.28	5.72	0.00	265
B1.25	56.36	3.67	5.47	5.68	940
b0.5B1.0	52.83	3.47	5.08	3.20	1017
b0.5B1.25	55.83	3.79	4.95	3.64	1205
b0.5B1.5	57.28	3.87	5.12	4.18	1393
b0.5S1.25	57.32	3.82	5.58	4.36	1141
b0.5S1.5	58.94	4.06	5.98	4.71	1317
b0.25B1.25	54.07	3.71	5.50	3.53	1073
b0.75B1.25	59.75	3.95	5.53	3.72	1338
pva0.75B1.25	57.18	4.18	5.41	4.81	3865
s0.75B1.25	68.48	4.73	6.30	4.47	1764

Note: ¹Fiber cost is based on market prices obtained from the authors' survey of domestic suppliers in China.

(1) Normalization of the value matrix

Based on the nature of the evaluation indicators, K_1 – K_4 are considered positive indicators (higher values correspond to better performance), while K_5 is a negative indicator (lower values are preferable). After normalizing the positive and negative indicators using Eqs. (8) and (9), respectively, a standardized decision matrix is obtained.

$$x_{ij} = \frac{k_{ij} - \min(k_{ij})}{\max(k_{ij}) - \min(k_{ij})} \quad (8)$$

$$x_{ij} = \frac{\max(k_{ij}) - k_{ij}}{\max(k_{ij}) - \min(k_{ij})} \quad (9)$$

where x_{ij} represents the standardized index value; k_{ij} represents the initial value of the evaluation index; $\max(k_{ij})$ and $\min(k_{ij})$ are the maximum and minimum values of k_{ij} , respectively. To ensure the validity of each indicator's data, a small constant of 0.0001 is added to every value.

(2) Weight of indicators

For AHP indicator weights, judgment matrices were constructed following established methods [53,54], listed in Table 8. Local weights, derived from the principal eigenvector, passed consistency checks with Eq. (10), and the results are listed in Table 9. Global weights were then calculated by Eq. (11), with final coefficients provided in Table 10.

$$CR = \frac{(\lambda_{max} - n)}{(n - 1)R_I} \quad (10)$$

where CR represents the consistency ratio, λ_{max} represents the maximum eigenvalue of the judgment matrix, R_I represents the average random consistency index, which can be obtained from standard.

$$\alpha_G = \alpha_c \times \alpha_m \quad (11)$$

where α_G represents the global weight, α_c and α_m represent the weights of indicators from criterion level and the sub-criterion level, respectively.

Table 8: Criterion level judgment matrix.

Indicators	Mechanical Performance	Economic Performance	Weight
Mechanical performance	1	2	0.6667
Economic performance	0.5	1	0.3333
Consistency Check	The maximum eigenvalue is 2, the value of CR is 0.052, and the consistency test is passed.		

Table 9: Sub-criterion level judgment matrix: basic mechanical properties.

	K ₁	K ₂	K ₃	K ₄	Weight
K ₁	1	1	0.5	0.5	0.1675
K ₂	1	1	1	0.3333	0.1800
K ₃	2	1	1	1	0.2817
K ₄	2	3	1	1	0.3708

Consistency Check The maximum eigenvalue is 4.117, the value of CR is 0.044, and the consistency test is passed.

Table 10: Summary of indicator weights based on analytic hierarchy process.

Judgment Level	Judgement Level Weights	Indicators Layers		Indicator Level Weights	Global Weight
		Indicators	Performance		
Mechanical performance	0.4934	A1	Compressive strength	0.1675	0.0826
		A2	Splitting tensile strength		
		A3	Initial flexural cracking strength		
		A4	Residual flexural strength		
Economic performance	0.1958	A5	Cost	0.3708	0.1829

As an objective weighting technique, the entropy weight method determines the weight of each evaluation indicator based on its degree of variation. The information entropy S_j is first calculated using Eq. (12), and the corresponding entropy weight is then obtained from Eq. (13).

$$S_j = -K \sum_{i=1}^m \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \ln \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (12)$$

$$\beta_j = \frac{1 - S_j}{\sum_{j=1}^n 1 - S_j} \quad (13)$$

where S_j represents the information entropy of the i -th evaluation indicator, K is a constant coefficient, $K = 1/\ln(m)$; x_{ij} represents the value of the j -th evaluation indicator in the i -th alternative.

To combine the weights derived from the AHP and entropy methods, a preference coefficient φ_j is introduced. This coefficient reflects the degree of preference given to the AHP-based weight for the j -th indicator, while $1 - \varphi_j$ represents the preference for the entropy-based weight. These coefficients are determined through least squares regression, as given in Eqs. (14) and (15):

$$\varphi_j = \frac{\beta_j^2}{\alpha_j^2 + \beta_j^2} \quad (14)$$

$$\delta_j = \sqrt{(\varphi_j \alpha_j)^2 + [(1 - \varphi_j) \beta_j]^2} \quad (15)$$

The entropy weights obtained from Eq. (13) are $\beta = [0.1568, 0.1552, 0.2108, 0.2739, 0.2033]$, and the preference coefficients determined via Eq. (14) are $\varphi = [0.4424, 0.4298, 0.4259, 0.5592, 0.6041]$. Substituting these values into Eq. (15) yields the composite weights $\delta = [0.1799, 0.1768, 0.2531, 0.2427, 0.1474]$.

(3) TOPSIS evaluation

By combining the weight coefficients with the standardized decision matrix, the weighted standardized decision matrix can be obtained, expressed in Eq. (16):

$$W = \begin{bmatrix} \delta_1 v_{11} & \delta_2 v_{12} & \cdots & \delta_n v_{1n} \\ \delta_1 v_{21} & \delta_2 v_{22} & \cdots & \delta_n v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \delta_1 v_{m1} & \delta_2 v_{m2} & \cdots & \delta_n v_{mn} \end{bmatrix} \quad (16)$$

Based on the weighted standardized decision matrix, the positive ideal solution W^+ and the negative ideal solution W^- for each evaluation indicator can be determined. They are defined respectively as the maximum and minimum values of each column vector in the matrix, as expressed in Eq. (17).

$$\begin{cases} W^+ = \max w_{ij} | i \in (1, m); j \in (1, n) \\ W^- = \min w_{ij} | i \in (1, m); j \in (1, n) \end{cases} \quad (17)$$

Therefore, the Euclidean distances from each alternative to the positive and negative ideal solutions D_i^+ and D_i^- can be expressed as Eq. (18):

$$\begin{cases} D_i^+ = \sqrt{\sum_{j=1}^n (w_{ij} - W_j^+)^2} \\ D_i^- = \sqrt{\sum_{j=1}^n (w_{ij} - W_j^-)^2} \end{cases} \quad (18)$$

To determine the distance between each alternative and the theoretically optimal value, the relative closeness degree T_i is employed for calculation and analysis, as shown in Eq. (19).

$$T_i = \frac{D_i^-}{D_i^- + D_i^+} \quad (19)$$

The TOPSIS evaluation results are presented in Table 11. The multi-scale hybrid fiber-reinforced concrete exhibits superior overall performance compared to plain concrete and single-fiber reinforced concrete, demonstrating a significant synergistic enhancement effect. Among all tested groups, s0.75B1.25 ranked first, followed by b0.5S1.5 and B1.25, confirming the effectiveness of high-modulus fiber reinforcement in achieving superior comprehensive performance. Notably, b0.75B1.25, though ranking fifth, represents the best-performing non-metallic hybrid system, offering additional advantages such as light weight, environmental friendliness, and corrosion resistance. For engineering applications where corrosion resistance is a primary concern, the b0.75B1.25 mixture presents a compelling alternative to steel fiber-reinforced systems. The TOPSIS framework thus provides a quantitative tool for balancing mechanical performance and economic cost in mixture selection for practice application.

Table 11: Performance evaluation of multi-scale hybrid fiber-reinforced concrete.

Groups	D_i^+	D_i^-	T_i	Rank
s0.75B1.25	0.204	0.897	0.814	1
b0.5S1.5	0.353	0.687	0.66	2
B1.25	0.523	0.632	0.547	3
b0.5S1.25	0.481	0.57	0.542	4
b0.75B1.25	0.467	0.55	0.541	5
b0.25B1.25	0.577	0.489	0.459	6
b0.5B1.5	0.598	0.504	0.458	7
pva0.75B1.25	0.678	0.495	0.422	8
b0.5B1.25	0.676	0.459	0.404	9
b0.5	0.79	0.459	0.368	10
b0.5B1.0	0.723	0.41	0.362	11
PC	0.872	0.392	0.31	12

4 Conclusions

Based on the experimental investigation and analytical discussion presented in this study, the following key conclusions can be drawn:

- (1) The hybridization of micro and macro fibers significantly enhances the mechanical performance of concrete. The optimal mixture (0.75% micro steel fibers + 1.25% BFRP minibars) improved compressive

and splitting tensile strengths by up to 32.0% and 48.7%, respectively, compared to plain concrete. The synergistic effect is closely governed by the elastic modulus and volume fraction of the fibers.

- (2) A quadratic function describes the relationship between the hybrid fiber reinforcement index and mechanical properties more accurately than conventional linear models. An optimal reinforcement index range of 0.3–0.5 was identified, offering a quantitative basis for performance-oriented mixture design.
- (3) The TOPSIS-based multi-criteria evaluation, integrating mechanical and economic indicators, confirms that multi-scale hybrid fiber-reinforced concrete exhibits superior overall performance, with group s0.75B1.25 achieving the highest comprehensive score. This validates the effectiveness of combining high-modulus micro steel fibers with BFRP minibars. Among non-metallic hybrid systems, group b0.75B1.25 demonstrates the best performance, offering a viable corrosion-resistant alternative with balanced mechanical properties and cost.
- (4) This study provides a systematic experimental characterization, an improved quadratic predictive model, and a balanced evaluation methodology for BFRP minibar-based hybrid FRC. The integrated framework enables rational design that reconciles mechanical performance with economic cost, offering a practical reference for the optimization of BFRP minibar-reinforced concrete in engineering applications.

It should be acknowledged that the present study focused primarily on mechanical characterization and did not systematically evaluate the workability of fresh concrete mixtures, which may influence fiber dispersion and thus affect mechanical performance, particularly at high total fiber volume fractions. Future work will address this limitation by comprehensively examining the coupled effects of multi-scale basalt fibers on workability, microstructure, mechanical properties, and durability of concrete.

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Ethics Approval: Not applicable.

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Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process
BFRP	Basalt Fiber-Reinforced Polymer
COV	Coefficient of Variation
FRC	Fiber-Reinforced Concrete
HFRC	Hybrid Fiber-Reinforced Concrete
PO	Polyolefin
PP	Polypropylene
PVA	Polyvinyl Alcohol
RI	Reinforcing Index
SEM	Scanning Electron Microscopy
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

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