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Synergistic Enhancement of High-Strength Concrete's Mechanical Strength Through the Utilization of Steel, Synthetic, and Hybrid Fiber Systems

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Abstract

This investigation addresses the notable gap in understanding the effects of fiber hybridization on concrete performance. The study's primary objective is to enhance the mechanical characteristics of high-strength concrete by incorporating a blend of steel and synthetic fibers. A detailed examination of 192 specimens, categorized into eight distinct groups, was conducted. This analysis focused on the roles of macrosteel and PP fibers in preventing significant cracks and micro-PVA and PP fibers in managing smaller-scale cracking. These specimens underwent stringent testing processes to evaluate the impact of fiber content, limited to a 1% concentration for macrofibers, on the compressive strength (CS) and flexural tensile (FTS) strength of the concrete. The results reveal that integrating steel fibers into concrete mixtures marginally enhances the CS (typically by 4–8%). In contrast, the incorporation of microsynthetic fibers (namely, PVA and PP), was observed to decrease the CS. This finding underscores the complexities inherent in the interaction between fibers and concrete. To support these findings, the study employed advanced nonlinear modeling techniques, concentrating on the interplay between various fiber types and their contributions to concrete strength. The developed models exhibit considerable predictive accuracy. The models showed the significant effect of macro-PP fibers on CS, especially when combined with steel fiber of length 40 mm. This specific blend produces a synergistic effect, notably enhancing the concrete's strength. Overall, this research provides crucial insights into the optimization of fiber-reinforced concrete mixtures, advancing the field by proposing enhanced mechanical performance strategies.

Keywords Compressive and flexural strength, Crack control optimization, Fiber hybridization, High-strength concrete, Nonlinear modeling

1 Introduction

1.1 Background

In the recent development of concrete materials, the strategic hybridization of fibers emerges as a pivotal factor in enhancing mechanical properties, particularly when compared to the use of monofibers. This technique plays a crucial role in addressing the issue of crack propagation within concrete structures (Abbas & Iqbal Khan, 2016; Abbas et al., 2023). The approach involves a multi-scale interposition (at the macroscale, larger cracks are effectively controlled by the integration of macrofibers). The hybrid fibrous systems are specifically designed to resist the expansion of significant cracks, thereby promoting the structural integrity of the concrete (Deng et al., 2020). On the microscale, the focus shifts to the containment of

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finer, less visible cracks. Microfibers are employed here, targeting these tiny fractures that, while small, can significantly impact the overall durability of the concrete (Abellan-Garcia et al., 2023). This thorough attention to both macro- and microlevel crack prevention is critical in advancing the field of concrete technology, providing a more robust, reliable, and durable material (Abellán-García et al., 2024). The innovative synergy of these two fiber types in a hybrid format represents a significant leap in material engineering, offering a comprehensive solution to one of the longstanding challenges in concrete reinforcement.

1.2 Related Studies

In the literature, Benthur and Mindess (2006) shed light on the nuanced fabrication of hybrid composites, which ingeniously integrate multiple fiber types within a single matrix. This form of composite construction is distinguished by its synergistic characteristics, drawing strength and ductility from the diverse properties of its constituent fibers. The concept of fiber hybridization in fiber-reinforced concrete (FRC) is a relatively recent development (Das et al., 2020). This innovative approach involves the combination of different fiber types, each chosen based on specific objectives and performance criteria. One primary motive for such hybridization is cost-effectiveness, where the blend of fibers aims to optimize both economic and structural efficiency (Khan et al., 2022a). Another driving factor is the enhancement of specific properties of the base concrete material (Ahmad et al., 2021). Recent advancements have demonstrated that carbon fibers, when used in FRC, significantly improve toughness compared to steel fibers (Yoo & Banthia, 2019). Conversely, steel fibers are the preferred choice when the primary requirement is enhancing strength (Jayakumar et al., 2022).

However, the most notable aspect of this hybridization lies in the synergistic interaction between different fiber types, particularly carbon and steel fibers. When used concurrently, these fibers compensate for their limitations in unreinforced concrete, leading to a composite material with superior strength and toughness (Dehghani & Aslani, 2020). This synergy refers to the phenomenon, where the combined effect of multiple components yields results superior to the sum of their individual effects (Zainal et al., 2022). Applied to hybrid fiber concrete, this principle suggests that the interplay between short and long fibers results in an improved tensile response (Li et al., 2021). The performance of the hybrid fiber concrete surpasses what would be expected from simply adding the effects of each fiber type used independently. This synergy not only enhances the mechanical properties of the concrete but also introduces a new dimension in the design and application of FRC, allowing for more versatile and robust construction materials (Ahmad & Zhou, 2022).

In FRC, the strategic integration of different types of fibers plays a critical role in enhancing the material's properties. One category of fiber, known for its strength and stiffness, primarily contributes to increasing the initial stress resistance and maximizing the ultimate strength of the concrete (Bankir & Sevim, 2020; Jen et al., 2016). In contrast, a more flexible type of fiber is utilized to bolster toughness and strain capacity, particularly in the aftermath of cracking (Ahmad et al., 2022; Ahmed et al., 2021). The balanced incorporation of these fibers is key. The stronger, stiffer fibers are used in smaller quantities, serving to arrest the development of microcracks at a microstructural level (Alrekabi et al., 2017). This results in a notable improvement in the tensile strength of the composite. Conversely, the larger, more flexible fibers are introduced to effectively manage the propagation of larger, macrocracks, thereby significantly augmenting the composite's overall toughness (Ahmad et al., 2022).

Furthermore, the synergistic effect of combining these fibers is evident in the enhancement of various properties of FRC (Banthia et al., 2014; Singh & Rai, 2021; Teng et al., 2018). While one fiber type may improve factors such as ease of production and resistance to plastic shrinkage, the other enhances the hardened mechanical properties (Bankir & Sevim, 2020). Despite the prevalent use of single-fiber types in commercial FRC, the limited efficacy of such systems in mitigating crack opening and deflection is increasingly recognized (Bhogone & Subramaniam, 2021; Naser et al., 2019; Zheng et al., 2022). Consequently, the focus of recent research has shifted towards exploring hybrid fiber-reinforced concrete, especially combinations like synthetic and steel fibers, carbon and polypropylene fibers, as well as carbon and glass fibers (Karim & Shafei, 2022; Khan et al., 2018; Zhong & Zhang, 2020). These studies aim to optimize the performance of these hybrid systems.

Another critical aspect under investigation is the influence of the concrete matrix's characteristic strength on FRC's performance. Research into the pullout mechanisms of fibers has underscored the importance of matrix composition and microstructure in determining fiber bond strength (Abbas, 2021; Abbas & Khan, 2016; Noorvand et al., 2022). Current studies (Abbas et al., 2022; Cao et al., 2020; Madandoust et al., 2015) concentrate on various factors such as the type and volume of cement, sand content, maximum aggregate size, and the use of mineral admixtures to understand their impact on FRC's behavior. This holistic approach to fiber and matrix interaction is crucial for advancing the field of concrete technology.

The efficacy of short fibers in bridging microcracks is attributed to their slender structure and higher quantity within the concrete mix, especially when compared to their long, thicker counterparts at equal fiber volume (Cui et al., 2023). This characteristic becomes particularly relevant during the initial stages of tensile loading, where microcrack formation is predominant (Pereira et al., 2012). Here, the short fibers play a pivotal role in boosting the concrete's tensile strength. As these microcracks evolve and coalesce into larger macrocracks, the role of long fibers becomes increasingly critical (He et al., 2022). Their function transitions to enhancing ductility and, to a certain extent, tensile strength, providing a more stable response even after peak stress is reached (Caggiano et al., 2015; Khan et al., 2022b). However, as the crack width expands, the contribution of short fibers diminishes due to their gradual pullout from the concrete matrix. A conventional reinforcement, which typically arrests major cracks at a single point and scale, the random distribution of fibers of varying types and sizes within the concrete matrix offers a more comprehensive crack control (Akcay & Ozsar, 2019; Banthia et al., 2014; Christopher et al., 2023). This method ensures that cracks are managed at multiple zones and sections, depending on the specific characteristics of the fibers used. A concise overview of studies focusing on this multi-fiber approach is succinctly presented in Table 1, highlighting the breadth of research in this area.

1.3 Objectives and Novelty of the Study

The earlier summarized literature review conclusively demonstrates that researchers focusing on enhancing the ductility of concrete with fibers have considered a restricted set of variables. These primarily encompass macrofibers, the proportion of fiber content, the fiber's aspect ratio, and the independent strength characteristics of the concrete. Moreover, there is a notable scarcity of studies exploring the combined use of ultrafines and fibers to augment both ductility and durability in concrete. Particularly, the role of inert fillers in conjunction with fibers, as a means to improve durability, has not been comprehensively investigated.

This study introduces a novel methodology for enhancing the mechanical properties of high-strength concrete by hybridizing steel and synthetic fibers in a manner that has not been extensively explored in previous research. Unlike prior studies, which often focus on individual fiber types, the current approach synergistically combines macrohook-ended steel fibers with macropolypropylene fibers to address macro-level cracks while incorporating micropolyvinyl and polypropylene fibers to manage micro-level cracking. This hybridization not only fills a critical gap in understanding fiber interactions but also demonstrates superior performance compared to using single-fiber types. By analyzing 192 test specimens across eight distinct groups and maintaining macrofiber volumes at a maximum of 1%, our research explores various microfiber percentages to assess their impact on both flexural and compressive strengths. In addition, we utilize advanced nonlinear models to provide a comprehensive evaluation of how these fiber types and their interactions influence concrete performance. This novel integration and detailed analysis mark a significant advancement over existing methods.

2 Experimental Campaign

2.1 Materials

In this research, we utilized ordinary Portland cement (Type I PC, compliant with ASTM C 150 standards) as the principal binding agent. The study also incorporated silica fume (SF) as a supplementary cementitious material. In addition, micro-quartz (MQ), an ultrafine filler, was integrated into the concrete formulations to bolster both strength and durability aspects. The median grain sizes for PC, SF, and MQ were noted at approximately 13.0 µm, 8.0 µm, and 3.5 µm, respectively. The detailed physicochemical characteristics of these fine powders are systematically cataloged in Table 2, while Fig. 1a graphically represents the distribution of their grain sizes, providing a comprehensive overview of their dimensional attributes.

Scanning electron microscopy (SEM) imagery (Fig. 2) reveals the distinct morphologies and size distributions of various fine powders used in this study. In (a), the MQ particles are predominantly amorphous in shape, with their sizes varying between 2 and 5 µm. Contrasting these, the SF particles, depicted in Fig. 2b, display a blend of smooth and coarse-textured spherical forms, averaging around 10 µm in diameter. This finding is notably larger than the typical SF particle sizes, generally under 1 µm (Kosmatka et al., 2002). Furthermore, Fig. 2c also illustrates the irregular, polyangular shape of ordinary PC particles, whose dimensions span from 1 to 20 µm. In this investigation, the concrete mixtures' workability was enhanced using a specialized superplasticizer (Glenium 51, a modified polycarboxylic ether polymer). The formulation of this superplasticizer contains a dry extract concentration of 36%, and it possesses a specific gravity of 1.1. The determination of the optimal dosage for this superplasticizer in the concrete mixture was based on a calculated ratio, which involved the dry extract percentage (D.E.) relative to the weight of the cement (%, wt.), ensuring the mixture achieved maximal workability. The optimization of this ratio was critical to formulating a concrete mixture that exhibited superior workability characteristics.

Table 1 Overview of the research on HyFRC

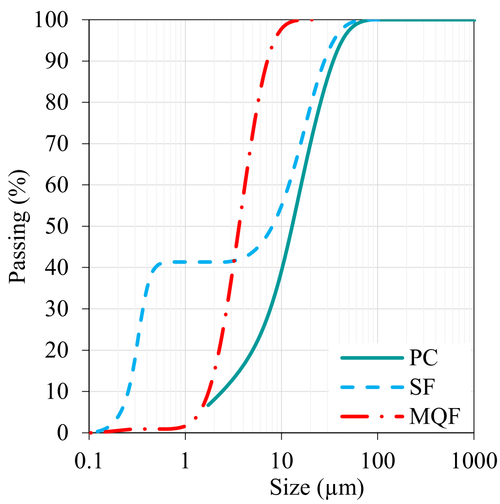
Ref	Hybrid system of fibers	Key conclusion
Walton & Majumdar, 1975)	PP–Ny–Gl–As–Ca	The integration of both organic and inorganic fibers significantly enhanced the material's tensile strength and impact resistance
Glavind & Aarre, 1990)	St–PP	The hybridization of fibers in the concrete composite results in a marked increase in its ultimate tensile strain
Larsen & Krenchel, 1990)	St–PP	Exposure to the hybrid composite samples for a decade has led to an increase in their fracture energy by up to 40%
Feldman & Zheng, 1993)	St–PP	The inclusion of steel fibers resulted in an enhancement of the ultimate tensile strength, while the integration of polypropylene fibers boosted the capacity for post-peak strain
Komloš et al., 1995)	St–PP	The use of hybrid fiber in concrete reinforcement has been shown to yield a superior impact strength and an improved response after cracking
Nam-Wook et al., 2000)	St–PP	The process of hybridization has markedly enhanced the material's resistance to the onset of initial cracking and its overall toughness
Horiguchi & Sakai, 1999)	St–PVA	The employment of hybrid fiber-reinforced concrete has led to an improvement in the deflection of the first crack while maintaining the same level of flexural toughness
Soroushian et al., 1993)	PP–PE	Hybridization has resulted in enhancements in both the flexural strength and toughness of the materials, proving particularly effective under impact loading conditions
Mobasher & Li, 1996)	Al–Ca–PP	The hybridization process has led to a significant increase in peak load capacity, showing a 75% enhancement compared to concrete reinforced with a single type of fiber, specifically polypropylene fiber
Stroeven et al., 2001)	Ca–St–PP	The incorporation of steel fiber through hybridization has notably enhanced the composite's toughness and its pullout resistance
Ramanalingam et al., 2001)	St–PVA (Short and long)	Hybridization has notably enhanced both the ultimate load capacity and the post-peak ductility of the material
Sun et al., 2001)	St–PP–PVA	By integrating varying lengths of steel fiber, shrinkage strains were reduced, and the permeability of the hybrid fiber-reinforced concrete also decreased
Hua et al., 2000)	Ca–PP	The hybridization of carbon and polypropylene fibers has led to an improvement in the fatigue properties of concrete
Lawler et al., 2002)	St–PP	The permeability of hybrid fiber-reinforced mortars, when subjected to load and displaying cracks, was observed to decrease
Banthia & Sheng, 1990)	Ca–St	The incorporation of steel fibers resulted in enhanced strength, while the addition of carbon fibers contributed to improved toughness in composites
Banthia & Soleimani, 2005)	St–CMP–CIP–PP	In normal-strength concrete subjected to flexural toughness tests, CIP fibers demonstrated a superior strain capacity compared to that of CMP fibers
Banthia & Gupta, 2004)	St–CMP–PP	In high-strength matrices, it has been observed that only a limited number of combinations exhibit a synergistic effect
Banthia & Sappakittipakorn, 2007)	St (different sizes)	Significantly enhanced toughness was noted when larger-diameter crimped steel fibers in hybrid composites were partially substituted with smaller-diameter crimped steel fibers
Banthia et al., 2014)	St (different types)–CNF	Hook-ended fibers exhibited markedly superior performance compared to double-deformed fibers. In addition, the formation of macrocracks revealed a decline in the efficiency of cellulose fibers
Chasioti & Vecchio, 2017)	St (different types)	The hybridization of fibers in concrete has led to an enhancement in both post-peak compressive and tensile behaviors, showing a notable improvement over concrete reinforced with a single type of fiber

PP Polypropylene, *Ny* Nylon, St: Steel, *Gl* Glass, *As* Asbestos, *Ca* Carbon, *PVA* Poly Vinyl Alcohol, *GS* Galvanized Steel, *Al* Alumina, *PE* Polyethylene, *CMP* Carbon Mesophase Pitch-based, *CIP* Carbon Isotropic Pitch-based, and *CNF* Cellulose Natural Fiber

Table 2 Physical and chemical characteristics of the utilized fine powders

Powder	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	Na_2Oeq (%)	SO_3 (%)	LoI (%)	RD (–)	Fineness m^2/kg
PC	20.2	5.49	4.12	65.43	0.71	0.26	2.61	1.38	3.14	373
SF	93.2	0.20	0.03	0.72	0.14	0.07	< 0.01	5.4	2.27	19,000
MQ	99.5	0.20	0.03	0.01	–	–	–	–	–	16,500

LoI Loss on ignition, *RD* Relative density



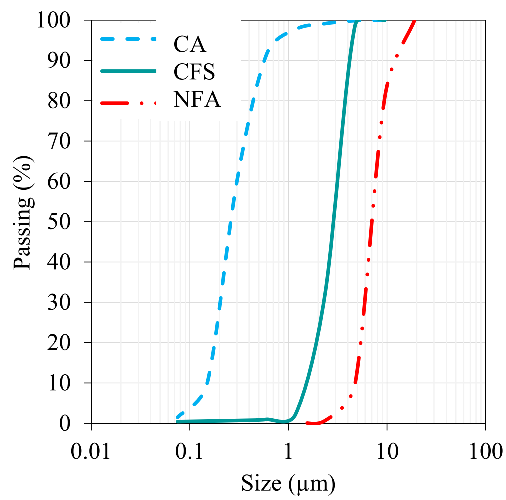


Fig. 1 Distribution of grain sizes in **a** fine powders and **b** aggregates

In the composition of the concrete mixes for this study, two distinct sand types were utilized, differentiated by their particle sizes: crushed fine aggregates (CFA) and natural fine aggregates (NFA). These aggregates exhibited fineness moduli of 4.66 (CFA) and 1.47 (NFA). When these were combined in a ratio of 65% NFA to 35% CFA, the resulting blended fine aggregate had a fineness modulus of 2.54. In addition, coarse aggregates (CA), limited to a maximum size of 10 mm, were incorporated into all the concrete mixtures. The distribution of grain sizes for these aggregates is graphically represented in Fig. 1b, and their physical properties are comprehensively detailed in Table 3. This approach to aggregate selection and blending was integral to achieving the desired structural and workability characteristics of the concrete.

Five types of fibers [two kinds of steel fibers [SS (St-40/65) and SL (St-60/80)], Poly Vinyl Alcohol (PVA), and two types of Polypropylene (PPI and PPA)] were used in this study. The properties of fibers are summarized in Table 4.

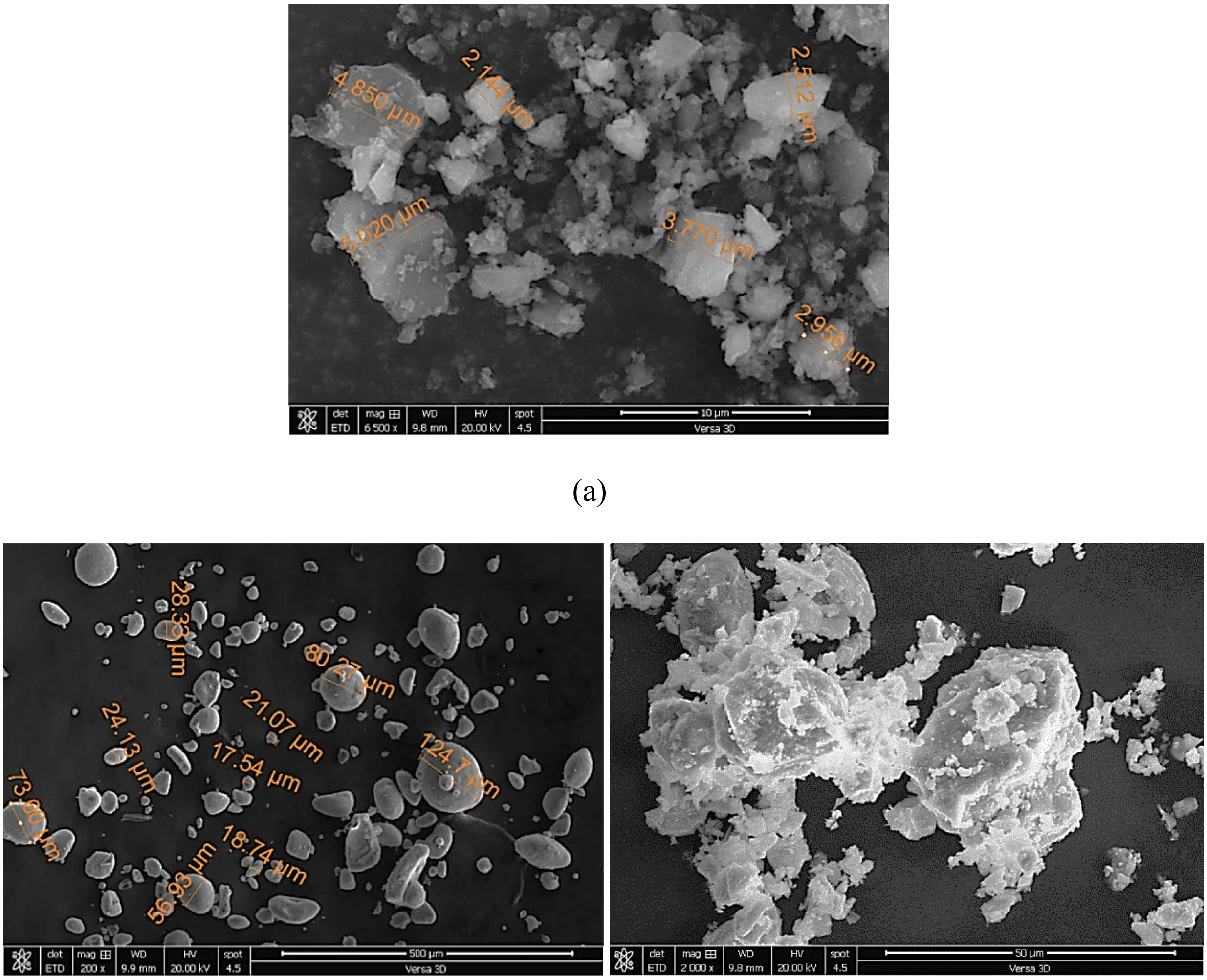
2.2 Methods

2.2.1 *Manufacturing the Concrete Mixes*

To prepare the plain concrete mixes, aggregate components were initially blended in a standard concrete mixer, incorporating absorption water to ensure consistency. This step was followed by a dry mix of fine powders to achieve uniformity. The subsequent addition of water and SP solution was thoroughly mixed, incorporating a 3-min blend, a pause, and a final 2-min mix. In contrast, the fabrication of fiber-reinforced concrete systems involved an extended 5-min blend to evenly distribute fibers. Here were adopted, mixing dry materials first, then adding a predetermined SP dosage until homogeneity was achieved. Fibers were then introduced, ensuring their complete integration into the mix. Ensuring the even distribution of fibers of the fresh concrete was a crucial part of our methodology. To accomplish this, we implemented a meticulously controlled mixing process, which involved carefully coordinating the sequence and timing of fiber incorporation. Fibers were gradually added to the concrete mixture, accompanied by continuous stirring to prevent clumping and promote thorough dispersion. Moreover, we extended the mixing duration to ensure the fibers were evenly spread throughout the concrete matrix. This method was validated through both visual inspections and workability consistency tests, confirming that the fiber distribution in the fresh concrete was uniformly achieved. Upon completion of mixing, the concrete was cast into molds, forming cylindrical specimens with dimensions of 100 mm diameter and 200 mm length for compression tests. Surface smoothing was performed with a trowel, and a plastic sheet was used to retain moisture. All concrete mixes were cured under standard curing conditions.

2.2.2 *Composition Details of Mixes*

In the present experimental study, we prepared two distinct sets of fiber-reinforced concrete mixtures, alongside their respective plain equivalents for comparison. The initial set focused on a hybrid fiber system, incorporating steel fibers with varying geometries. Whereas, the second set was designed to explore the effects of a combined steel and synthetic fiber



(a)

(b) (c)

Fig. 2 SEM images of **a** MQ, **b** SF, and **c** PC

Table 3 Physical features of the employed aggregate

Aggregate type	RD	Absorption %	Density kg/m^3
WS	2.63	0.77	1725
CS	2.68	1.52	1552
CA	2.65	1.45	1570

system. The first set of mixes entailed the preparation of seven distinct concrete mixtures. The study's mix design was based on a water-to-cementitious materials ratio of 0.30, targeting a slump range of 150 ± 25 mm for the fiber-less concrete variant. The fibers employed in the mixes varied in length (40 and 60 mm) and diameter (0.62 and 0.75 mm) and coded as SF and FL, respectively. These mixtures were categorized as Control-1, FL1.00, (FS0.25 + FL0.75), (FS0.35 + FL0.65), (FS0.50 + FL0.50), (FS0.75 + FL0.25), and FS1.00, each denoting a specific fiber composition. Detailed proportions of components in each mix are systematically outlined in Table 5, providing a comprehensive view of the varying formulations used in the study. The optimization of HySFRC was achieved through a strategic selection of fiber ratios and dosages. To bolster strength, high dosages of steel fibers (up to 1.0%) were employed, while varying the dosages of synthetic fibers (up to 0.75%) aimed at enhancing crack resistance. Various fiber combinations were meticulously tested to assess their synergistic effects, ensuring that total dosages remained within practical limits to

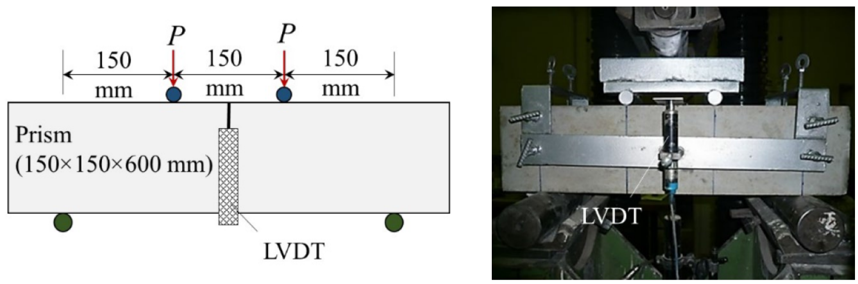
Table 4 Properties of steel and PVA fibers

Fiber type	Code	Length (mm)	Diameter (mm)	Aspect ratio	Young's Modulus (GPa)	Tensile strength (MPa)
Hook-ended Steel	SS	40	0.62	65	210	1250
	SL	60	0.75	80	210	1250
Poly Vinyl Alcohol	PVA	12	0.040	300	38	1300
Polypropylene	PPI	18	0.032	563	3.8	380
	PPA	48	0.85	56	4.7	400

Table 5 Composition details of the studied HySFRC

Set	Mix No.	Fibrous system	Fiber (%, vol.)					Total
			St-60/80	St-40/65	PVA	PPI	PPA	
1	M1	CTRL-I	–	–	–	–	–	–
	M2	St-60/80(1.0)	1	–	–	–	–	1.0
	M3	St-60/80(0.75) + St-40/65(0.25)	0.75	0.25	–	–	–	1.0
	M4	St-60/80(0.65) + St-40/65(0.35)	0.65	0.35	–	–	–	1.0
	M5	St-60/80(0.5) + St-40/65(0.5)	0.5	0.5	–	–	–	1.0
	M6	St-60/80(0.25) + St-40/65(0.75)	0.25	0.75	–	–	–	1.0
	M7	St-40/65(1.0)	–	1	–	–	–	1.0
2	M8	CTRL-II	–	–	–	–	–	–
	M9	PVA(0.25)	–	–	0.25	–	–	0.25
	M10	PVA(0.5)	–	–	0.5	–	–	0.50
	M11	PVA(0.75)	–	–	0.75	–	–	0.75
3	M12	PPI(0.125)	–	–	–	0.125	–	0.125
	M13	PPI(0.25)	–	–	–	0.25	–	0.25
	M14	PPI(0.5)	–	–	–	0.5	–	0.50
	M15	PPI(0.75)	–	–	–	0.75	–	0.75
4	M16	PPA(0.25)	–	–	–	–	0.25	0.25
	M17	PPA(0.5)	–	–	–	–	0.5	0.50
	M18	PPA(0.75)	–	–	–	–	0.75	0.75
	M19	PPA(1.0)	–	–	–	–	1	1.0
5	M20	PPI(0.25) + PPA(1.0)	–	–	–	0.25	1	1.25
	M21	PPI(0.5) + PPA(1.0)	–	–	–	0.5	1	1.50
	M22	PPI(0.25) + PPA(0.75)	–	–	–	0.25	0.75	1.0
	M23	PPI(0.5) + PPA(0.75)	–	–	–	0.5	0.75	1.25
6	M24	St-60/80(0.75) + PVA(0.1) + PPI(0.15)	0.75	–	0.1	0.15	–	1.0
	M25	St-60/80(0.8) + PVA(0.1) + PPI(0.1)	0.8	–	0.1	0.1	–	1.0
	M26	St-60/80(0.85) + PVA(0.05) + PPI(0.1)	0.85	–	0.05	0.1	–	1.0
	M27	St-60/80(0.9) + PVA(0.05) + PPI(0.05)	0.9	–	0.05	0.05	–	1.0
7	M28	St-60/80(0.75) + PVA(0.25)	0.75	–	0.25	–	–	1.0
	M29	St-60/80(0.85) + PVA(0.15)	0.85	–	0.15	–	–	1.0
8	M30	St-60/80(1.0)	1	–	–	–	–	1.0
	M31	St-60/80(1) + PVA(0.15)	1	–	0.15	–	–	1.15
	M32	St-60/80(1) + PVA(0.25)	1	–	0.25	–	–	1.25

preserve both the concrete's performance and workability. Furthermore, the challenges encountered during the addition of various fiber types, including steel and synthetic fibers, are crucial to address. For instance, in mixes M3–M7 and M9–M11, achieving uniform distribution required significantly extended mixing times.



(a) (b)

Fig. 3 Four-point load testing: **a** schematic diagram and **b** experimental setup

This was particularly true for mixes with multiple fiber types (M24–M27), where maintaining concrete workability, while ensuring consistent fiber dispersion proved difficult. Integrating different types of polypropylene fibers, such as PPI and PPA, further complicated uniformity (M20–M23). Steel fibers were prone to segregation, and synthetic fibers demanded meticulous handling to avoid entanglement. These challenges were mitigated by refining our mixing techniques and carefully timing fiber addition to optimize distribution and enhance the performance of the high-strength concrete.

In the second set of mixes, a total of 25 concrete mixtures were prepared and tested to explore the impact of hybrid fiber reinforcement on the mechanical properties of high-performance concrete. These mixtures, as detailed in Table 5, included both singular and combined use of synthetic and steel fibers. The investigation was designed to assess the influence of different fiber types on concrete characteristics. Specifically, the study utilized micropolypropylene (PPI) fibers, micropolyvinyl alcohol (PVA) fibers, macropolypropylene (PPA) fibers, and macrosteel (SF) fibers in various configurations. The objective was to determine how these different mono- and hybrid fiber combinations affect the mechanical properties of high-strength fiber-reinforced concrete. The detailed configurations of these fiber-reinforced mixtures are presented in Table 5, highlighting the diverse range of synthetic and steel fibers tested in high-strength concrete formulations. The composition of each mix is notable for its consistency across all variants, with water, PC, CS, WS, and CA (10 mm size), present in quantities of 164, 500, 251, 467, and 1052 kg/m^3, respectively.

2.2.3 Experimental Protocols

2.2.3.1 Testing Under Uniaxial Compression In the experimental setup of this research, cylindrical specimens were first coated with a uniform layer of sulfur mortar. This preparatory step was crucial to ensure that both the top and bottom surfaces of the specimens were level, facilitating an even distribution of the load during the uniaxial compression test. The mechanical properties, specifically the 28-day elasticity modulus and compressive strength of the cement-based materials, were evaluated in compliance with ASTM C469 and ASTM C39 standards, respectively. The tests were carried out using a ToniTech universal compression testing machine, boasting a capacity of 3000 kN. To accurately measure both in-plane and transverse strains, the setup included the attachment of two linear variable displacement transducers (LVDTs) and compressometer rings, positioned around the central height of the samples (approximately 100 mm). The loading applied in these tests was meticulously controlled, with parameters set to 2.5×10^{-3} mm/s for displacement and 0.25 MPa/s for load. To ensure the validity and reliability of the results, each compression test was replicated two to three times, with the mean of these trials being reported in the study's findings. In cases where the results displayed reasonable reproducibility, only two specimens were tested.

2.2.3.2 Testing Under Four-Point Flexural Loading The flexural strength of SFRC specimens was evaluated using prismatic specimens measuring 150×150×600 mm. These specimens underwent a four-point bending test, progressively loaded until failure, as depicted in Fig. 4a, b. To gauge deflection, two Linear Variable Differential Transformers (LVDTs) were strategically placed beneath the midpoint of the beam. The loading rate was consistently maintained at 0.2 mm/min. An examination of the beams' flexural toughness included monitoring the declining post-cracking load value after reaching peak load. Calculation of the flexural members' ductility or energy absorption capacity was based on the load–deflection curves, illustrated in Fig. 3c, following the methodology outlined in Khan et al. (2017). The area under the curve, extending

Table 6 Summary of the experimental results

Set	Mix No	Fibrous system	CS (MPa)	% diff. w.r.t. CTRL	FTS (MPa)	% diff. w.r.t. CTRL
I	M1	CTRL-I	77.7	–	9.4	–
	M2	S60/80(1.0)	82.0	5.57	15.1	60.04
	M3	S60/80(0.75) + S40/65(0.25)	81.5	4.84	16.2	71.61
	M4	S60/80(0.65) + S40/65(0.35)	84.1	8.20	19.2	103.41
	M5	S60/80(0.5) + S40/65(0.5)	83.2	7.05	16.1	70.27
	M6	S60/80(0.25) + S40/65(0.75)	80.4	3.44	16.5	75.09
	M7	S40/65(1.0)	82.3	5.90	14.9	58.27
II	M8	CTRL-II	82.0	–	9.6	–
	M9	PVA(0.25)	72.3	− 11.87	9.8	1.84
	M10	PVA(0.5)	65.7	− 19.87	9.9	2.62
	M11	PVA(0.75)	62.5	− 23.77	10.3	7.11
III	M12	PPI(0.125)	71.7	− 12.60	9.8	1.12
	M13	PPI(0.25)	65.7	− 19.87	10.0	3.22
	M14	PPI(0.5)	69.8	− 14.91	10.3	6.34
	M15	PPI(0.75)	67.8	− 17.39	10.4	8.15
IV	M16	PPA(0.25)	77.5	− 5.49	9.7	0.81
	M17	PPA(0.5)	73.2	− 10.73	9.4	− 2.49
	M18	PPA(0.75)	77.0	− 6.10	10.2	6.09
	M19	PPA(1.0)	79.3	− 3.37	10.4	8.21
V	M20	PPI(0.25) + PPA(1.0)	73.0	− 11.01	10.2	5.97
	M21	PPI(0.5) + PPA(1.0)	73.8	− 10.04	11.1	14.93
	M22	PPI(0.25) + PPA(0.75)	80.6	− 1.79	10.5	8.71
	M23	PPI(0.5) + PPA(0.75)	76.4	− 6.91	10.7	10.95
VI	M24	S60/80(0.75) + PVA(0.1) + PPI(0.15)	85.6	4.35	14.9	54.32
	M25	S60/80(0.8) + PVA(0.1) + PPI(0.1)	83.8	2.15	14.2	46.77
	M26	S60/80(0.85) + PVA(0.05) + PPI(0.1)	85.5	4.23	18.0	86.57
	M27	S60/80(0.9) + PVA(0.05) + PPI(0.05)	85.8	4.59	18.9	96.39
	M28	S60/80(0.75) + PVA(0.25)	85.8	4.59	15.9	64.55
	M29	S60/80(0.85) + PVA(0.15)	77.5	− 5.53	15.8	63.43
VII	M30	S60/80(1.0)	85.2	3.86	24.6	154.73
	M31	S60/80(1) + PVA(0.15)	88.8	8.25	28.5	195.15
	M32	S60/80(1) + PVA(0.25)	83.4	1.61	22.8	136.38

to the point of maximum stress, was derived from empirical curves. This area is indicative of the energy absorption capacity (or ductility) of the SFRC. In this study, the flexural strength, denoted as σ, [$\sigma = (3PL)/(2bd^2)$], where P represents the peak load applied to the specimen, L is the span length of the prism, b stands for the width of the specimen, and d refers to its depth. As depicted in Fig. 3, $L = 450$ mm; $b = d = 150$ mm.

3 Experimental Results

Table 6 presents a comprehensive summary of both the compressive and flexural strengths exhibited by the investigated concrete mixes, along with the corresponding percentage variations relative to their respective control counterparts. Subsequent sections will present an in-depth analysis of these findings, providing a detailed discussion of the results.

3.1 Compressive Strength

3.1.1 Multiscale HySFRC

Fig. 4 presents the findings from a comparative analysis of compressive strength in plain concrete and SFRC containing varying proportions of steel fibers. Fig. 4a shows that the addition of steel fibers to high-performance concrete mixes has a positive impact on compressive strength, with enhancement percentages varying depending on the mix composition. The specific ratio and type of steel fibers used play a crucial role in determining the level of improvement. It was observed that both mono- and hybrid steel fiber blends marginally enhance the

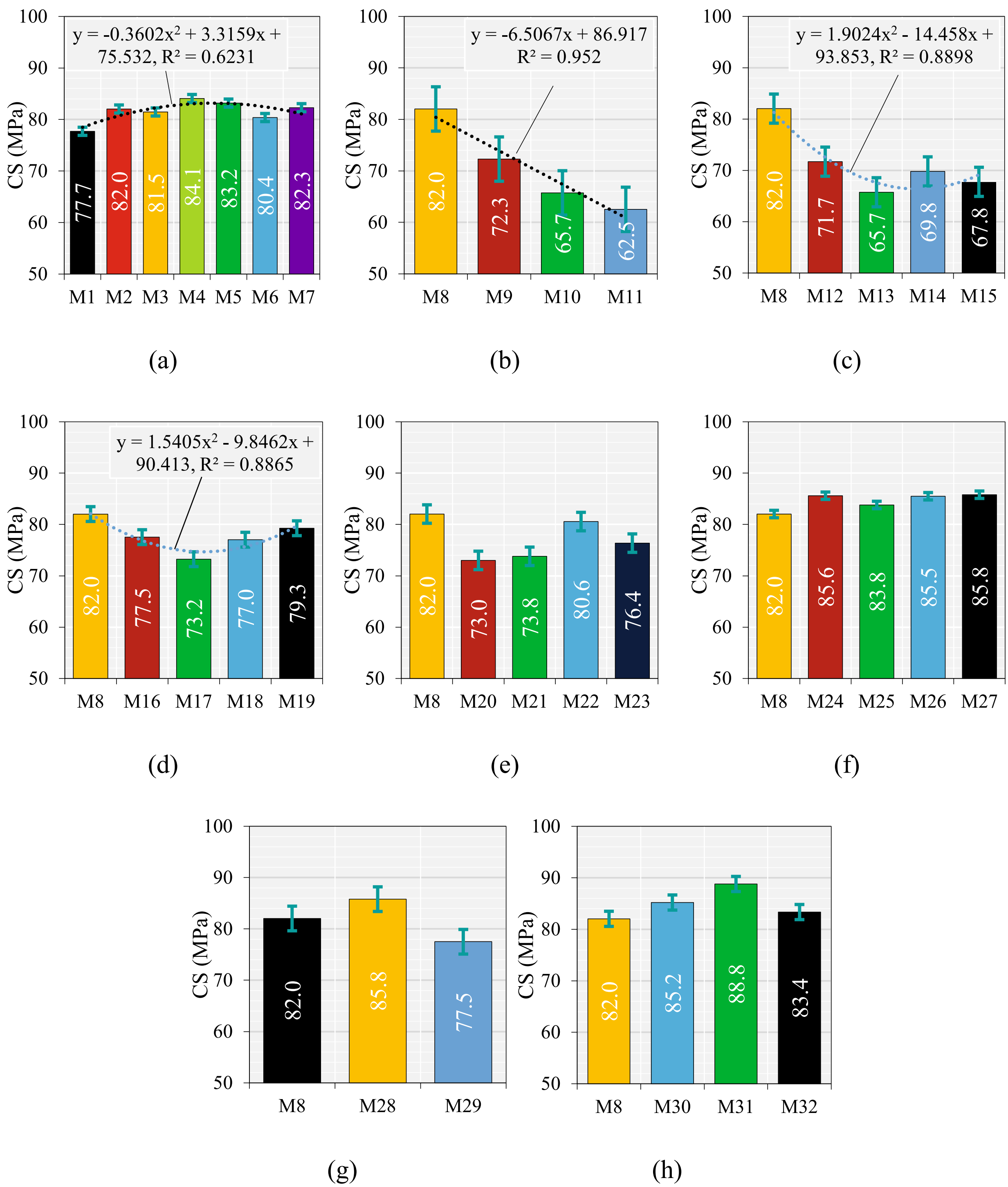


Fig. 4 Compressive strength of the studied concrete mixes: **a** Set-1, **b** Set-2, **c** Set-3, **d** Set-4, **e** Set-5, **f** Set-6, **g** Set-7, and **h** Set-8

compressive strength of concrete by approximately 4–8%. Notably, while monofiber mixes consistently displayed similar strength increases, an optimal composition of hybrid fibers M1 with S60/80(0.65) + S40/65(0.35) fibrous system was identified, yielding a peak strength increment of 8%. This marked enhancement in compressive strength is likely attributed to the fibers' ability to impede early crack formation, thus reinforcing the concrete's mechanical performance (Jen et al., 2016; Teng et al., 2018).

3.1.2 Multi-type HyFRC

3.1.2.1 Monosynthetic Microfibers Fig. 4b, c presents the outcomes of compression tests performed on plain concrete and monosynthetic fiber-reinforced concrete, incorporating varying proportions of PVA and PP fibers. The data indicate a notable decline in compressive strength when microsynthetic fibers are added to high-strength concrete, compared to the control mixture. This reduction in compressive strength becomes more pronounced with increasing concentrations of microsynthetic fibers. Specifically, the introduction of PVA fibers led to a 23% reduction in compressive strength for a 0.75% PVA fiber mixture relative to the control mix. Similarly, PP fiber mixtures exhibited a 20% decrease in compressive strength. The integration of PVA and PP fibers leads to a diverse range of negative impacts on compressive strength. The observed decline in the compressive strength of reinforced with PVA and PP fibers can be traced back to several key factors. The incorporation of these fibers impacts the concrete's hydration process, complicates the mix's workability, and induces irregular shrinkage and thermal responses (Öz et al., 2023; Yuan et al., 2020; Zhang et al., 2022). In addition, it causes changes in the volume and cohesion of the cement paste (Zhang et al., 2021).

3.1.2.2 Single and Combined Synthetic Fiber-Reinforced Concrete Fig. 4d, e illustrates the outcomes of compression tests performed on various concrete mixtures: (i) plain concrete, (ii) concrete reinforced with mono–macro-PP fibers, and (iii) concrete hybridized with micro-PP fibers at different concentrations. The study reveals an obvious decrease in compressive strength for the high-strength concrete when macro-PP fibers were added compared to the control mix. Specifically, the compressive strength exhibited a reduction of 10% with a 0.50% dosage of macro-PP fiber mixture. In contrast, the hybrid mixture of macro- and micro-PP fibers demonstrated an 11% reduction in strength for a blend comprising 1% macro-PP fiber and 0.25% micro-PP fiber. Interestingly, the compressive strength's decline varied with the dosage of macro-PP fibers, indicating a fluctuating pattern. This decrease is less pronounced in the hybrid mixture containing 0.75% macro-PP fiber combined with 0.25% and 0.5% micro-PP fibers, compared to mixtures with 1% macro-PP fiber and micro-PP fiber. This suggests that the addition of synthetic fibers does not inherently enhance compressive strength, as these fibers do not significantly arrest or delay crack formation. The synthetic material exhibits lower resistance to compressive load-bearing capacity than plain concrete. Despite the general reduction in compressive strength due to the addition of synthetic fibers, the hybrid mixture of 0.75% macro-PP fiber and 0.25% micro-PP fiber maintained a comparable level of compressive strength to the control mix. This observation aligns with the results presented by Azandariani et al. (Azandariani et al., 2023), underscoring its significance in the context of existing research. Furthermore, this finding underscores the complex impact of fiber inclusion on the concrete matrix's phases and suggests potential optimization strategies for fiber-reinforced concrete formulations.

3.1.2.3 Hybridization of Macrosteel and Microsynthetic Fibers Fig. 4f, g illustrates the outcomes of compression tests on various concrete formulations: plain concrete, and concrete enhanced with a blend of macrosteel and micro-synthetic fibers in varying proportions. The data indicates a progressive enhancement in compressive strength correlating with the increased incorporation of macrosteel fibers into the high-strength concrete, compared to the baseline mixture. Analysis of Fig. 4f reveals that increasing the amount of macrosteel fibers within the concrete mix yields a compressive strength boost ranging from 2% to 5% for varied fiber dosages. Specifically, a rise in macrosteel fiber content to a certain level results in a maximum increase of 4.5% in compressive strength relative to the plain concrete mix. This improvement in strength is attributed primarily to two factors: (i) the steel fibers' role in arresting crack development and thereby delaying the failure of the concrete structure (Khan et al., 2022b) and (ii) a higher concentration of steel fibers in the plain concrete matrix enhances the anchorage between the matrix and the fibers, leading to increased interlocking within the concrete matrix and the steel fibers (Benedetty et al., 2021). This synergy strengthens the overall structural integrity of the concrete.

3.1.2.4 Hybridization of Macrosteel and Micro-PVA Fibers The compression test results for plain concrete and concrete reinforced with a combination of macrosteel and micro-PVA fibers are illustrated in Fig. 4h. This figure highlights a notable enhancement in compressive strength correlating with the increased incorporation of macrosteel fibers in the high-strength concrete, compared to the baseline mixture. Specifically, an upward trend in compressive strength is evident, peaking at an 8% increase for mixtures containing 1% macrosteel fibers and 0.15% micro-PVA fibers. Remarkably, the addition of hybrid macrosteel and micro-PVA fibers to the high-strength concrete did not result in any significant reduction in performance across most tested dosages. This finding can be attributed to two primary factors: first, the steel fibers effectively inhibit the progression of major cracks, thereby delaying the concrete's failure (Wang et al., 2020), and

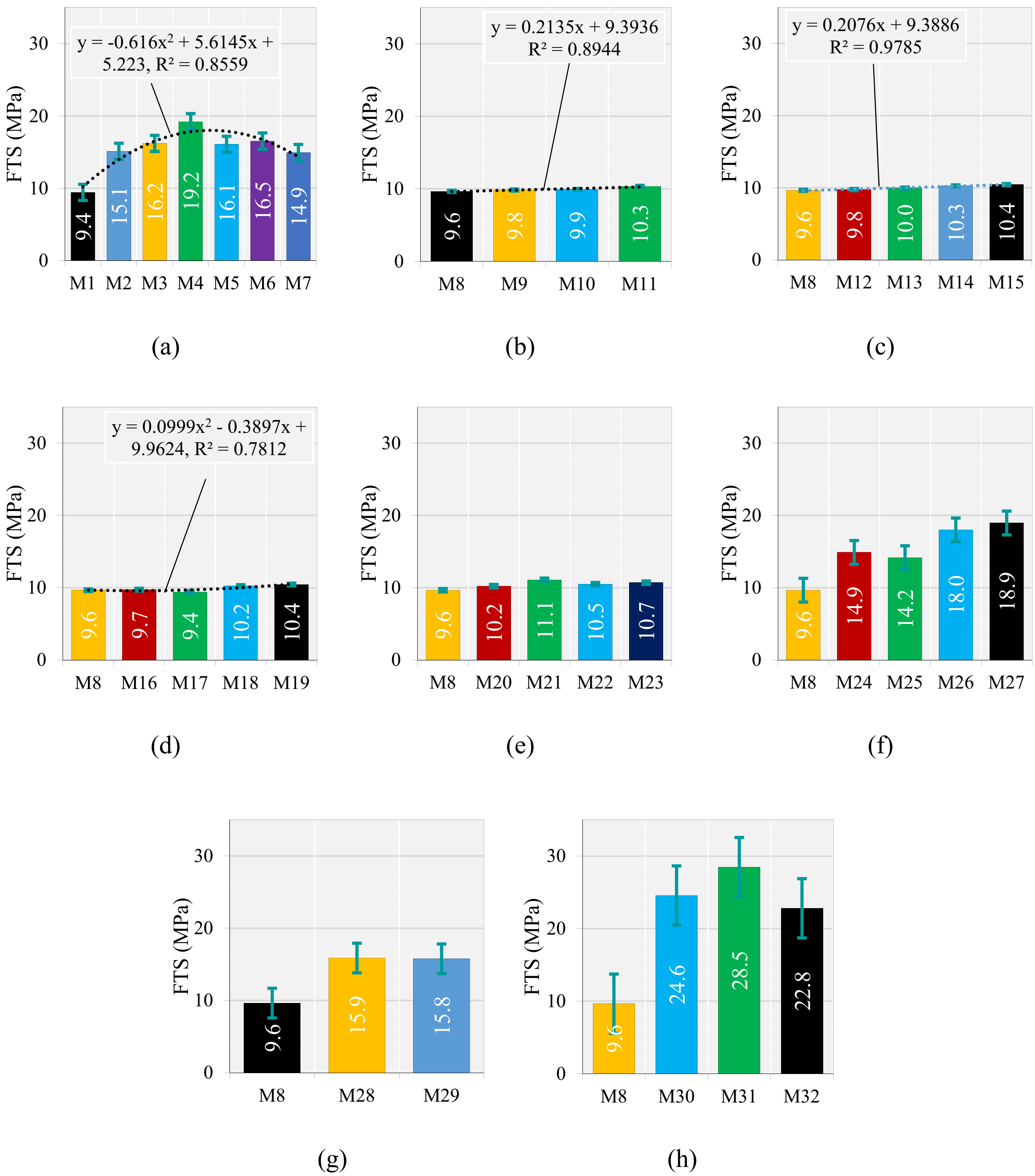


Fig. 5 Flexural tensile strength of the studied concrete mixes: **a** Set-1, **b** Set-2, **c** Set-3, **d** Set-4, **d** Set-5, **e** Set-6, **f** Set-7, and **g** Set-8

second, the increased presence of steel fibers enhances the interlocking of the concrete matrix, improving the anchorage between the matrix and the fibers (Gong et al., 2022). adding macrosteel and micro-PVA fibers to high-strength concrete increases compressive strength by up to 8%, due to improved crack inhibition and fiber-matrix interlocking.

3.2 Flexural Tensile Strength

3.2.1 Multiscale HySFRC

The experimental outcomes of the flexural testing, conducted via the four-point loading as detailed in Sect. 2.2.3.2, are depicted in Fig. 5. Fig. 5a illustrates a significant enhancement of about 60–100% (See Table 6) in the flexural strength of fiber-reinforced mixtures, using steel fibers and plain concrete, depending on the fiber combination utilized. The analysis reveals that mixtures containing only monofibers exhibit a maximum increase in flexural strength, achieving up to a 60% improvement when compared to plain concrete. In contrast, the hybridization of fibers results in a more pronounced increase in flexural strength, slightly more than 100%. Notably, the M4 mixture [with "S60/80(0.65) + S40/65(0.35)" fibrous system] stands out, showing the greatest increase in flexural strength among all the mixtures examined.

3.2.2 Multi-type HyFRC

3.2.2.1 Monosynthetic Microfibers Fig. 5B, c displays the outcomes of flexural testing conducted on concrete samples enhanced with varying proportions of PVA and PP fibers at 28 days. The figure illustrates an increase in flexural strength across different fiber concentrations compared to plain concrete. Interestingly, the incorporation of both PVA and PP fibers resulted in a comparable rate of enhancement in flexural strength, as evidenced by the nearly equivalent slopes of their respective trendlines. In detail, concrete samples with 0.75% volume of mono–micro-PVA fibers exhibited an up to 7% improvement in flexural strength, whereas those with a similar volume of PP fibers showed up to an 8% enhancement, each benchmarked against plain concrete. Integrating PVA and PP fibers into concrete significantly enhances its resistance to cracking, which results in an elevated flexural tensile strength of the concrete (Li et al., 2018).

3.2.2.2 Single and Combined Synthetic Fiber-Reinforced Concrete Fig. 5d, e displays the data from flexural testing conducted using a four-point loading system. This figure illustrates the variations in flexural strength across different concentrations of macro-PP fibers and micro-PP fibers, measured at 28 days. Notably, an enhancement in flexural strength was observed with increasing fiber content in most mixes, except for the PPA 0.50 mix, which deviated from this trend. The data indicates that the inclusion of 1% macro-PP fibers in the concrete mixture led to an increase in flexural strength by 7–8% compared to the baseline plain concrete. In terms of hybrid fiber compositions, those combining macro-PP and micro-PP fibers demonstrated superior flexural strength relative to plain concrete. Specifically, a mix with 1% macro-PP fiber and 0.5% micro-PP fiber showed the most significant improvement, exhibiting up to a 14% increase in flexural strength over plain concrete. Another hybrid mix, containing 0.75% macro-PP fibers and 0.5% micro-PP fibers, also showed a notable increase in flexural strength, ranging between 10–11%. It is noteworthy that none of the concrete mixtures, regardless of whether they were reinforced with hybrid or monosynthetic fibers, exhibited deflection hardening behavior in these high-strength concrete formulations.

3.2.2.3 Hybridization of Macrosteel and Microsynthetic Fibers Fig. 5f, g details the flexural strength variations at 28 days for concrete mixtures with varying concentrations of macrosteel fibers, and both micro-PP and micro-PVA fibers. This data highlights a significant enhancement in flexural strength attributable to the varying levels of fiber addition. In particular, an increase in macrosteel fiber content to 0.9% resulted in an impressive 96% enhancement in flexural strength compared to plain concrete. Similarly, a 0.75% inclusion of macrosteel fibers led to a 50% increase in strength relative to the control mix. These improvements are likely due to the fibers' ability to delay the onset of cracking and subsequently arrest crack propagation, thereby elevating the failure load threshold of the fiber-reinforced concrete mixtures.

3.2.2.4 Hybridization of Macrosteel and Micro-PVA Fibers Fig. 5h presents the outcomes of flexural strength assessments. These results, particularly focused on the 28-day age mark, detail the flexural strength variations in concrete reinforced with differing proportions of macrosteel and micro-PVA fibers. Notably, the flexural strength enhancements in the concrete mixtures correspond directly with the increased concentrations of steel fibers. Specifically, a mixture containing 1% macrosteel fibers and 0.15% micro-PVA fibers exhibited a near 200% surge in flexural strength compared to plain concrete. A notable increase of up to 150% in flexural strength was observed with the addition of 1% macrosteel fibers alone. This substantial improvement can be attributed to the fibers' role in delaying the onset of cracks and enhancing the load-carrying capacity of the concrete by arresting crack propagation. Furthermore, the phenomenon of fiber bridging contributes significantly to improved deflection characteristics in fiber-reinforced concrete, resulting in superior flexural strength compared to its plain counterpart.

4 Predictive Models

This study evaluated the effects of different fiber systems on concrete's compressive and flexural strengths using the general-purpose statistical software Minitab version 9.0 (Banthia et al., 2014; Naser et al., 2019). The analysis employed a design of experiments methodology, which

Table 7 Variables and R^2 of the developed models

	α_o	α_1	α_2	α_3	α_4	α_5	α_{11}	α_{22}	α_{33}	α_{44}	α_{55}	α_{13}	α_{14}	α_{34}	α_{45}	R^2
CS (MPa)	77.2	5.3	4.2	− 23.5	− 35.0	3.5	1.0	0.3	4.8	30.9	− 3.3	31.0	82.1	− 98.0	17.5	85.2
FTS (MPa)	9.47	− 25.6	37.8	2.9	1.8	0.4	36.5	−31.9	2.8	− 0.5	0.42	19.3	50.9	− 293	− 0.23	87.9

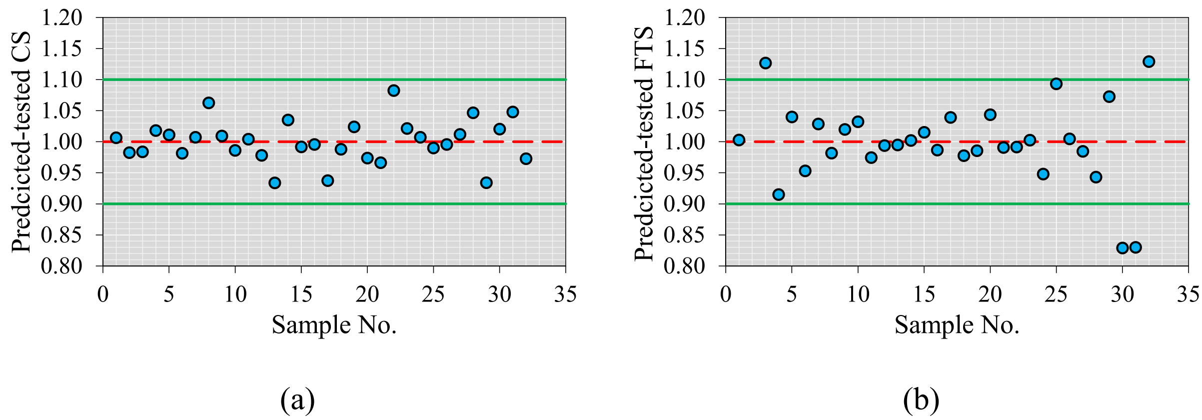


Fig. 6 Predicted vs. tested results for: **a** CS and **b** FTS

involves quantifying each variable's impact through a specialized response function that considers their nonlinear relationships. This method also enabled the generation of predictive models for the observed behaviors, constrained by the experimental parameters. In addition, it allowed for the assessment of optimized experimental conditions through isoresponse functions. The response surface model, denoted as 'y', was formulated using five distinct continuous variables, following the equation provided:

$$y = \alpha_o + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3 + \alpha_4 x_4 + \alpha_5 x_5 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2 + \alpha_{33} x_3^2 + \alpha_{44} x_4^2 + \alpha_{55} x_5^2 + \alpha_{13} x_1 x_3 + \alpha_{14} x_1 x_4 + \alpha_{34} x_3 x_4 + \alpha_{45} x_4 x_5$$

In this model, the variables x_1, x_2, x_3, x_4 and x_5 represent the volumetric content (%) of St-60/80, St-40/65, PVA, PPI, and PPA fibers, respectively. The α constants are integral to the model's structure. Notably, these variables were treated as part of a continuous, infinite range. Table 7 details these variables concerning the compressive strength (CS) and flexural tensile strength (FTS) of concrete, alongside the determination coefficient (R^2), which quantifies the model's predictive accuracy against experimental data. Significantly, certain interactions (i.e., x_1x_3, x_1x_4, x_3x_4 and x_4x_5) are included in the formula, highlighting their insignificant effect on the model's response. Moreover, both established nonlinear models exhibit high R^2 values, confirming their robust predictive capability.

In Fig. 6, the established model's predictive accuracy for both CS and FTS responses is illustrated. This graphical representation reveals that, for all tested samples, the ratio of predicted to actual values approximates unity. Specifically, in the case of CS, the predicted-to-tested ratios predominantly fall within a narrow span of 0.93 to 1.08, exhibiting a mean value (μ) of 1.0 and a coefficient of variance (CV) of 3.4%. This indicates a high level of precision in the model's predictions for compressive strength. In contrast, the FTS responses demonstrate a slightly broader variation, with most predicted-to-tested ratios lying between 0.95 and 1.10. The mean value for FTS stands at 1.01, accompanied by a higher CV of 8.9%, suggesting a modest increase in variability compared to the CS predictions. These findings underscore the model's robustness in predicting material behaviors under different fibrous systems, reflecting its potential applicability.

In this research, the previously established models were employed to explore the impact of various fiber types and their interplay on the model's responses, focusing particularly on the CS and FTS of concrete. The results of this analysis are presented in Fig. 7 (Pareto chart of the standardized effects). Fig. 7a highlights those polypropylene macrofibers (PPA) exhibit the most pronounced standardized effect on CS, underscoring their critical role

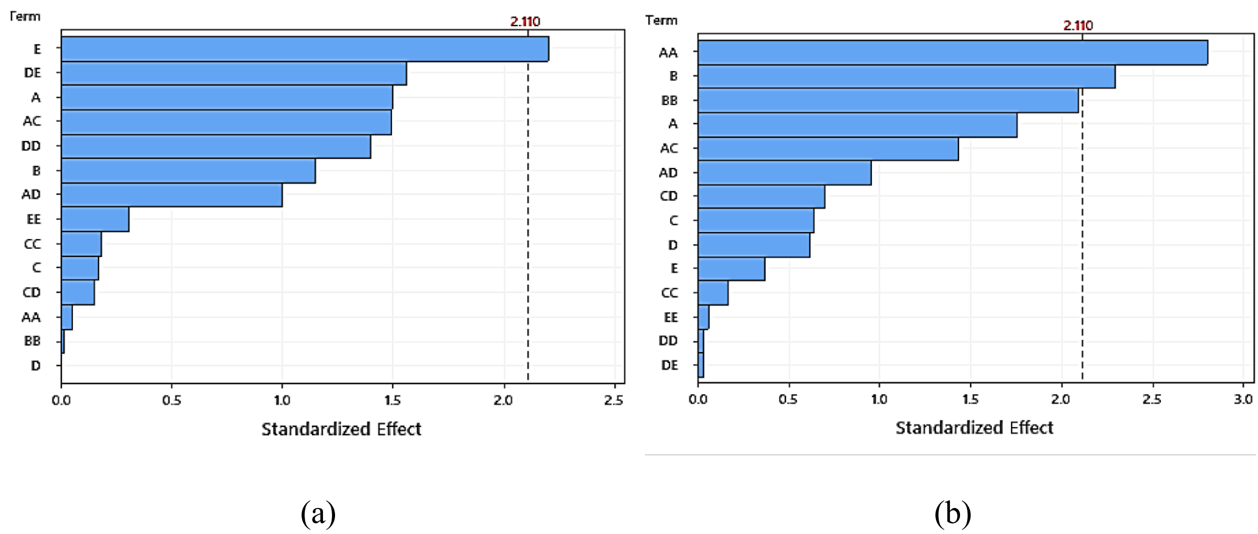


Fig. 7 Pareto-chart for the standardized effects ($\alpha = 5\%$) for: (a) CS, and (b) FTS. (Note. A: x_1; B: x_2; C: x_3; D: x_4; E: x_5)

in enhancing this property. While PPA fibers alone contribute significantly to strength, steel fibers (St-60/80 and St-40/65) also contribute positively, though less markedly than PPA fibers. Moreover, the interaction of steel fibers St-40/65 with PPA fibers, denoted as the DE term, emerges as significant. This interaction implies a synergistic effect, enhancing the CS more effectively than when these fibers are used independently. Conversely, certain interactions and specific fiber types exhibit negative standardized effects, such as the 'EE', 'CC', and others. These negative effects might suggest detrimental interactions or incompatibilities, potentially due to issues like inadequate fiber dispersion or adverse impacts on the concrete's hydration process. A deeper investigation into these negative influences is crucial to understand their root causes. For an optimized concrete mixture design, the findings recommend prioritizing PPA fibers, especially in combination with St-40/65 fibers while being cautious about or avoiding those fibers and combinations with adverse effects. Although the Pareto chart offers insights into the magnitude of these effects, it doesn't convey their statistical or practical significance. Therefore, further statistical analyses, including p value computations and confidence interval estimations, are necessary to ascertain these findings' robustness. In addition, practical tests are recommended to validate these outcomes, ensuring that the optimized fiber mix enhances compressive strength without compromising other vital properties like workability, durability, and cost-effectiveness.

Analyzing Fig. 7b, it becomes evident that the St-60/80 fibers, designated as 'A', have a paramount positive standardized effect on the flexural tensile strength of concrete. This finding suggests that the use of St-60/80 fibers alone markedly enhances this strength attribute, with the effect size notably surpassing a standardized effect of 2.0. Beyond this, other fiber types, represented by singular alphabetic terms, such as B, C, D, and E, also contribute positively, though their impact is less pronounced compared to the St-60/80 fibers. In addition, the interaction terms, denoted by two-letter combinations like AB, AC, AD, etc., reveal the cumulative effects of combining different fibers. These interactions display a range of effects, with some exhibiting beneficial impacts, while others appear less significant. Concluding this data, it becomes clear that among the fibers examined, St-60/80 fibers stand out as the most critical in boosting the flexural tensile strength of concrete. Moreover, the data indicates the presence of synergistic effects when different fibers are combined, as shown by the positive standardized effects of certain interaction pairs. However, it is also apparent that not all fiber combinations yield positive strength increases, suggesting that certain fibers may not synergize effectively or that their combined effect does not significantly surpass their contributions. For a comprehensive analysis, further examination would typically include assessing the statistical significance of these effects, evaluating confidence intervals, and conducting additional tests to ascertain the reliability of these findings. Moreover, it is crucial to consider the practical implications of these results, focusing on the cost-effectiveness and long-term durability of these fiber combinations in real-world scenarios.

5 Conclusions and Perspective

This research explores enhancing high-strength concrete through the integration of steel and synthetic fibers. It primarily investigates the synergistic impact of combining various hooked-end steel fibers with synthetic ones. The study utilizes macrosteel and polypropylene fibers for major crack prevention, along with micropolyvinyl and polypropylene fibers for finer crack control. Analyzing 192 specimens across eight categories, the project rigorously tests the influence of these fibers, capped at 1% for macrotypes, on the concrete's flexural and compressive strength. Advanced nonlinear modeling supports this investigation, focusing on the interplay and individual contributions of different fiber types. Based on the current research, the following conclusions can be drawn:

1. Incorporating steel fibers into concrete mixtures can enhance compressive strength by 4–8%, while the addition of microsynthetic fibers like PVA and PP tends to decrease it, reflecting their impact on concrete's mechanical properties.
2. Concrete mixtures reinforced with fibers, particularly hybrid types, show significant flexural strength improvements, up to 200% in some cases, largely due to better crack resistance and the efficiency of fiber bridging.
3. Using an experimental design methodology, this study created models that accurately predict concrete strength, incorporating fiber content and model constants, as evidenced by high R^2 values (85.2% for CS and 87.9% for FTS) and precise predicted-to-tested ratios.
4. Utilizing established models, the research determined that PPA fibers significantly influence concrete's compressive strength. PPA and St-40/65 fibers in combination exhibit a synergistic effect, enhancing strength, while some fiber mixtures negatively affect concrete properties.

Further statistical analysis and practical tests are recommended for validating these findings and ensuring the optimized fiber mix balances strength with workability, durability, and cost-effectiveness. Future research would also include a comprehensive investigation of rheology and durability issues, including resistance to cracking, freeze–thaw cycles, and chemical attack. In addition, a detailed examination of cracking patterns and failure modes in concrete reinforced with various hybrid fiber systems under diverse loading conditions would provide valuable insights into their long-term behavior and reliability.

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Author contributions
M.I.K: conceptualization, methodology, formal analysis, writing—original draft, and writing—review and editing. Y.M.A: methodology, formal analysis, validation, writing—original draft, and writing—review and editing. All authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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