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# Review of High-Strength Concrete Structures with Hybrid Fibers

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## Abstract

This work provides a thorough evaluation of high strength concrete (HSC) constructions augmented with hybrid fibers, emphasizing their mechanical properties and structural performance. High-strength concrete, characterized by a compressive strength of 55 MPa or greater, is extensively employed in contemporary construction, especially in skyscrapers, owing to its capacity to reduce column dimensions. Nonetheless, conventional HSC demonstrates deficiencies, such as inadequate tensile strength and ductility, which may jeopardize structural integrity. The integration of fibers into concrete mixtures has been increasingly prevalent during the past decade to tackle these issues. Recent research has investigated the utilization of diverse fiber types in hybrid combinations to enhance various performance attributes of HSC. This review consolidates research findings from 2021 onwards, emphasizing the role of hybrid fibers in improving the mechanical properties of high-strength concrete. The paper examines the ramifications of these advancements for future research and practical applications, highlighting the necessity for additional exploration of fiber interactions, performance assessments under varied conditions, and the establishment of standardized protocols for the utilization of hybrid fibers in construction. This review seeks to further the development of concrete technology and its utilization in high-performance constructions.

## Introduction

High-strength concrete is characterized by a compressive strength more than 50 MPa. High-strength concrete (HSC) is predominantly utilized in structures necessitating substantial load-bearing capacity, minimized member dimensions, and extended service life. High-strength concrete (HSC) with hybrid fibers is a sophisticated construction material engineered for enhanced mechanical

performance and durability. This composite material mitigates issues of brittleness, cracking, and durability under harsh conditions by integrating high-strength concrete with a mixture of several fiber types (hybrid fibers) [1]. Adding hybrid fibers consist of two or more fiber kinds, including steel, polypropylene, basalt, or glass fibers improve concrete performance at both micro and macro levels [2]. Using two kinds of fibers led to enhance two or more features of high strength concrete, such as:
1. Steel fibers enhance tensile strength and post-crack load-bearing capacity. 2. Polypropylene or basalt fibers mitigate shrinkage and micro-cracking during the curing process. 2. incorporation of hybrid fibers improves energy absorption and impact resistance. 3. Hybrid fibers reduce permeability and enhance resilience to environmental deterioration (e.g., freeze-thaw cycles, chlorine attack). 4. Fibers inhibit the beginning and spread of fractures by bridging both micro and macro fissures [3].

**Literature Review**

[4] examined the effects of hybrid fibers on high strength fiber-reinforced self-consolidating concrete (FRSCC). Nine mixtures with different fiber types and factors were tested, including slump flow, T50 time, and J-ring tests. A hyperbolic drying shrinkage prediction model was proposed, showing that hybrid fibers can reverse PVA fibers' reductions in compressive strength and increase flexural performances. The model predicts drying shrinkage with a suitable shrinkage halftime.

The high mechanical strength and ductility of fiber-reinforced ultra-high-performance concrete (UHPC) are advantageous to the loading capacity of the material when subjected to both static and dynamic stresses. The current study investigates the use of hybrid fiber reinforcement in ultra-high performance concrete (UHPC) in order to further improve the material's performance, particularly with regard to its crack restraint capability and flexural capacity. It was determined that four different combinations with single and hybrid fiber reinforcing were made. Fibers with three distinct lengths—six, ten, and fifteen millimeters—were integrated, but they all had the same diameter—0.2 millimeters—and the same volume dosage—2.5 percent. The study found that hybrid fibers in UHPC (Underground Polymer Composite) improved flexural performance and compressive strength, while single long fiber reinforcement resulted in lower flexural strength and fracture energy. The dynamic behavior of UHPC beams under low-velocity impact showed improved flexural response and better impact resistance, with a lower maximum and residual displacement compared to long fiber reinforcements [5]. While [6] focused on the performance of concrete specimens reinforced with different volume percentages of PVA and PP fibers. Portland cement was supplied by a local factory, and silica fume was supplied by Sika Egypt for Construction Chemicals Complying with ASTM C 1240. Concrete specimens were cast in wooden forms, including reinforcing steel cages, and subjected to moisture exposure for 28 days.

The results showed that all test beams failed in shear except for B14 and B15, which failed in flexural shear as shown in Figure1. The presence of PP fibers, PVA fibers, and hybrid fibers in concrete showed better ductility compared to non-fiber reinforced concrete specimens. The increase of these fibers resulted in higher tensile strength and a significant improvement in ductility. PVA fiber showed a relatively greater tensile strength and recovery effect in beams compared to PP fiber. This is consistent with previous studies reporting strength improvement as a result of using PVA. The study also found that adding PVA in 1.5% (B3) and 2.5% (B4) and hybrid fibers (1.5% PVA and 0.375% PP) without shear reinforcement (stirrups) contributed towards increasing shear capacity and ductility higher than that of the control beam with stirrups

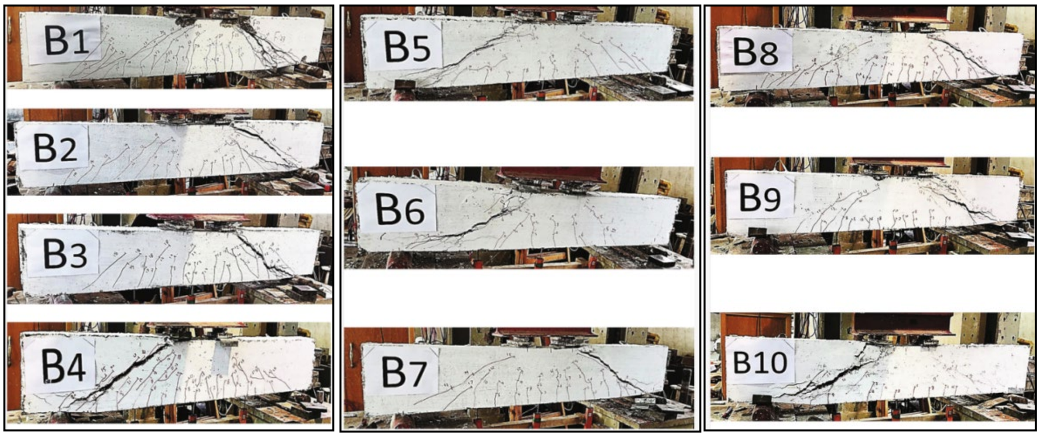


Figure 1 Crack pattern for tested specimens [6].

The authors recommend a combination of at least hybrid fibers (0.75% PVA and 0.75% PP) and stirrups reinforcement (7.5 Ø 6 /m) to achieve adequate shear behavior of hybrid fiber reinforced concrete beams. This combination, when adding silica fume to concrete, prevented sudden failure, improved shear strength and ductility, and formed several small flexural cracks prior to failure [6].

Thermal stability of natural fiber composites is crucial due to processing temperature, which affects their mechanical and thermal properties. Thermal analysis methods like Thermo gravimetric analysis (TGA), differential scanning calorimetric (DSC), and differential mechanical thermal analysis (DMA) are used to determine these properties. Recent advances in fiber treatment, exploration of new natural fibers, and hybridization have addressed some shortcomings in natural fiber reinforced composites. Surface treatment of natural fibers enhances their mechanical and thermal properties, improving fiber-matrix interfacial bonding, roughness, and wettability. However, some researchers found that surface treatments led to weakened thermal stability. Natural fiber reinforced polymer composites (NFRCs) use thermoplastic and thermoset polymers, with PLA being a popular choice due to its high strength and low elongation at break [7].

There is study found that increasing the volume fraction of carbon fiber, aramid fiber, and polypropylene fiber positively impacted the tensile and flexural strengths of Fiber Reinforced Concrete (HFRC). However, the compressive strength decreased linearly with increasing hybrid fiber volume fraction. The optimal volume fraction of hybrid fibers was 0.12%. The overall mechanical properties of HFRC with three types of fibers were better than a single type. The addition of carbon fibers and hybrid fibers significantly influenced energy consumption capacities. A uniaxial compression constructive mathematical model was established for stress and strain prediction [8]. [9] examined the effects of single steel fiber and hybrid steel fiber with various fibers on ultra-high performance concrete (UHPC) tensile specimens.

Results showed that hybrid fiber reinforced UHPC had good toughness damage characteristics, with the softening section significantly influenced by the type and volume content of fibers. The best toughening and crack resistance effect was achieved when the volume content of steel fiber was 1.5% and the volume content of PVA fiber was 1.0%. The predicted UHPC tensile σ-ω curves were in good agreement with the experimental results. In 2024, [10] investigated the flexural performance of reinforced high strength recycled aggregate concrete (RHRAC) beams by combining RAC with polyvinyl alcohol fiber (PVAF) and steel fiber (SF). Results show that SF increases flexural strength more than PVAF, while PVAF has a more significant effect on deformability. Hybrid fibers have superior effects on crack load, flexural capacity, and deformation capacity.

Yassin explored the structural behavior of super high-performance concrete (SHPC) with hybrid fibers of micro polypropylene (PP) and macro steel fiber (ST) as shown in Figure2, particularly with equal content. The study tests three types of fibers, focusing on workability, compressive strength, splitting tensile strength, and flexural behavior. The goal is to determine the optimal hybridization percentage for maximum structural and economic benefits.

Figure 2 Types of fibers used in Yassin's study [11].

The authors also investigated the mechanical properties of SHPC using ten mixtures of standard cubes and cylinders, as well as standard notched beams: following the Egyptian code ECP 203-2020. The materials were chosen based on common reports and guidelines, and the experiments were conducted according to ACI 544.8R-16, ACI 544.2R-17, ACI 544.9R-17, and BS EN 206:2013. The total number of specimens tested was 270, and the results were average for the research.

This paper explores the mechanical properties and flexural behavior of super high-performance concrete (SHPC) experimentally and analytically. The study involved ten mixtures with different fiber types and volume content, totaling 270 specimens. The results showed that the hybridization of micro polypropylene (PP) and macro-end-hooked steel (ST) fibers affected the flexural behavior and mechanical properties of SHPC.

The results were used to predict the splitting tensile strength (fsp) and modulus of rupture (fctr) for SHPC with each type of fiber. The formulae obtained were accurate and in good agreement with previous research results. Another founding was the additional ultimate moment due to the presence of fibers (Mnu-FRC) for all beams was predicted accurately. The compressive strengths fluctuated in a range close to those of plain concrete, possibly due to the voids and microscopic cracks produced by fibers. The study also found that increasing the amount of hybrid fibers increased the tensile splitting strength but decreased it due to the balling effect of the high-volume content of PP fibers. The flexural tensile strength increased more with macro-ST fibers than with micro-PP fibers. The study also found that both hybrid and polypropylene fibers can help reduce the cost and dimensions of reinforced concrete sections. For SHPC, both polypropylene and hybrid fiber-reinforced mixtures are more economical than ST fiber-reinforced mixtures. In conclusion, the optimal percentage for the fiber volume content for the hybrid of ST and PP is 1%, with 0.5% for each of the two kinds [11].

Qadir explored the use of hybrid fibers in high-strength concrete. The research uses metallic and natural fibers, with steel fibers being particularly strong for controlling cracking. Bio fibers like coir and palm are used to create composite materials that rival synthetic composites due to their renewability, biodegradability, and eco-friendliness. The study uses M50 grade concrete with a mix ration of 1:1.38:2.88. Fiber reinforced concrete beams have greater ultimate moment resistance compared to conventional RC beams. The mixture of 0.5% steel, 0.25% palm, and 0.25% coir hybrid fibers shows the most significant enhancement in residual strength parameters. The study suggests a new approach for predicting the structural characteristics of concrete using a multilayer feed forward neural network. Fibers are often used to manage cracking caused by plastic shrinkage, drying shrinkage, and water bleeding.

The study investigates the mechanical and structural characteristics of high strength hybrid fiber concrete (HFRHC), using materials such as Portland cement, fine aggregate, coarse aggregate, and water. The initial mix concrete was made with regular Portland cement, fine aggregate, coarse aggregate and drinking water. Super plasticizer was used as a crack arrester to prevent expansion of faults. The study found that HFRHC reinforced concrete had better compressive strength than concrete made solely of steel fibers. The compressive strength of hybrid composite increased from CC about 13.95% and 15.4% in 28 days to 11.43% and 11.94% for 90 days. The study also investigated the flexural toughness of composite fiber concrete reinforced to transmit stress over a fractured portion. The study found that adding only 1% of steel fiber (M1) raised compression strength by around 6.2%, while the maximum compressive strength rose by around 17.15% for the mix M4. The study also found that adding steel fiber to organic fiber only increased post-peak opposition, which greatly enhanced the flexibility characteristics of concrete made using these hybrid fibers [12].

Bindu, explored the behavior of high strength reinforced cement concrete with polypropylene and steel fibers. High strength concrete has less ductility, which can lead to brittle failure. Fibers are added to increase ductility and alter the manner of brittle collapse. Steel fibers are a cutting-edge material that significantly improves the material's durability, fatigue resistance, impact resistance, fracture resistance, and bending resistance. Polypropylene fibers are a popular choice due to their exceptional toughness and cost-effectiveness. They help reduce shrinkage cracking, improve the softening branch of load-displacement curves, and enhance ductility and toughness of concrete. Concrete can be strengthened by adding polypropylene fibers to prevent moisture- and heat-induced cracks, increase mix cohesiveness, and increase resistance to freezing and thawing. Concrete using hybrid fiber reinforcement (HFRC) demonstrates various fracture behavior and strain hardening. A hybrid composite with the appropriate volume ratio of high and low modulus fibers should demonstrate simultaneous improvements in ultimate strength, strain capacity, and fracture width properties. Polypropylene fibers can enhance electrical resistivity, permeability, and compressive strength. A 1.5% dose of polypropylene fibers is suitable for enhancing both compressive and flexural strength. The study focuses on the geometric properties of six rectangular RC beams, including three cubes, cylinders, and hybrid fiber reinforced concrete (HFRC) beams. The compressive strength of hybrid fiber reinforced concrete cubes increased by 15.22% compared to the control concrete cube. The ultimate load enhancement ratio (λ) was found to be 1.30, with the insertion of hybrid fibers enhancing the ultimate load capacity of HFRC beams.

The study concludes that the use of hybrid fibers in M60 concrete can improve its compressive strength, split tensile strength, and ultimate load bearing capacity [13-14] explored the use of steel fibers in concrete mix, focusing on combinations of polypropylene, high-density polyethylene, and basalt fibers. It also highlights the use of quaternary blends, such as cement, fly ash, GGBFS, and silica fume, to enhance concrete's mechanical properties and promote sustainability. The study also examines the effects of different fiber volume fractions, focusing on 0.5% steel fiber and 0.5% of another fiber type. HFRC is renowned for its reduced weight, sustainability, and enhanced performance, making it suitable for innovative construction projects. [15] investigated the use of hybrid fibers in enhancing the structural performance of reinforced concrete beams. The study found that a combination of 0.4% steel and 0.2% glass fiber significantly improved the performance of the beams compared to conventional RC beams. The research also used finite element analysis (FEA) to predict the outcomes of the experiments, which closely correlated with the experimental data. The study highlights the innovative approach of using hybrid fibers to enhance the structural performance of reinforced concrete beams. [16] explored the use of hybrid fibers, specifically basalt and steel fibers, to improve the mechanical properties of high strength reinforced concrete beams.

The research involved extensive experimental testing, focusing on optimal fiber content ratios and temperature effects. Results showed significant improvements in tensile strength and compressive strength under different conditions. The flexural behavior showed that a mix of 2% BF and 1% SF increased capacity by 27% at normal temperatures, while at high temperatures, it increased by 27.2%. The use of BF and SF also increased ductility, shifting the failure mode from shear to flexural failure. The study highlights the potential of hybrid fibers in enhancing the performance of high-strength reinforced concrete under varying temperature conditions.

Amsayazhi, has developed a hybrid fiber-reinforced concrete mix to enhance performance in beam-column connections. The mix, containing 0.3% glass fiber and 0.7% polypropylene fiber, creates a reinforced layer with high-strength concrete in the beam section. Four beam-column joints were cast with a dual-layer concrete design, demonstrating a 22.9% improvement in ultimate load-carrying capacity compared to control specimens. The study also found significant gains in ductility, structural strength, and load-carrying capacity, offering a robust solution to durability and performance challenges in reinforced concrete beam-column connections. Hybrid fiber-reinforced concrete (HFRC) combines two or more types of fibers in a single matrix, resulting in enhanced crack control, improved load-carrying capacity, reduced reinforcement congestion, and superior ductility. The study also focuses on the preparation of beam and column specimens for reinforced concrete structures, fabricated in steel molds with steel rods supporting the layers. Recent advancements in beam-column joint design have introduced neural network models to predict joint shear strength in reinforced concrete structures [17]. The name of the mixtures was listed in Table1 and the results shown in Figure3.

Table 1 MIX ID for tested specimens[17].

| MIX ID | Layer on top (mm) | Layer on bottom (mm) | Depth of HFRC(mm) |
|---|---|---|---|
| CC | 200 | / | / |
| BC-Q | 150 | 50 | Quarter |
| BC-H | 100 | 100 | Half |
| BC-F | 0 | 200 | Full |

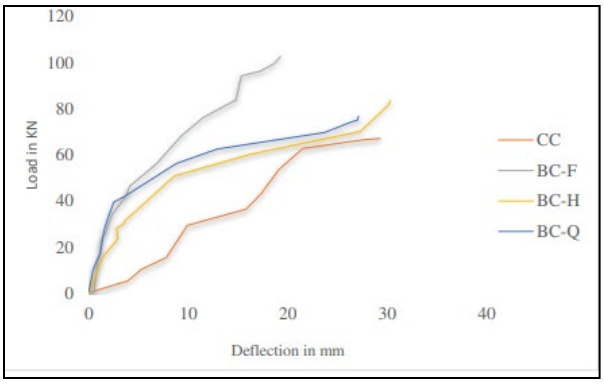


Figure 3 Load-deflection curve for tested specimens [17].

Moussa investigated the shear performance of high-strength concrete beams reinforced with carbon fiber-reinforced polymer (CFRP) bars. Thirteen beams were subjected to four-point stress to failure, emphasizing parameters such as shear span-to-depth ratio, longitudinal reinforcement ratio, transverse reinforcement ratio, and kind of longitudinal reinforcement. The results indicated that CFRP-reinforced HSC beams may experience rapid failure due to their brittle characteristics. The incorporation of longitudinal steel bars improved ultimate shear capacity, but an elevated longitudinal reinforcement ratio augmented ultimate shear strength. Both CFRP and steel-reinforced beams exhibited comparable shear capacity [18].

Another study investigated the impact of high temperature on the residual mechanical properties of steel-PVA hybrid fiber high-performance concrete (HFHPC). It involves preparing specimens with different ratios and mineral powder substitutions and subjecting them to controlled heating from ambient to 800°C. The results show that hybrid fibers enhance the residual strength and performance of concrete after high temperatures, supporting its application in high-temperature concrete applications. High temperatures have a detrimental effect on the performance of HFHPC; however, the utilization of fibers and mineral powders in a strategic manner can improve the performance of post-temperature concrete. It is recommended that future studies investigate the ideal mixing proportions as well as new materials[19]. [20]

This study investigates the flexural performance of ultra-high-performance fiber-reinforced concrete (UHPFRC) using four varieties of steel fibers at a constant 2% volume percentage. The main aim is to assess the influence of deformed steel fibers in hybrid reinforcement systems relative to straight steel fibers. The findings indicate that hybrid-reinforced UHPFRC often demonstrates superior compressive strengths, exhibiting minimum variance of around 10% among specimens. Augmenting beam thickness improves flexural strength while diminishing deflection capacity in uniaxial UHPFRC beams. Increased incorporation rates of hooked-end (h) steel fibers diminish the flexural strength and toughness of UHPFRC, especially at greater deflections. Conversely, twisted steel fibers (t3 and t6) preserve toughness at incorporation rates of 1% and 1.5%, respectively, albeit moderate decreases in flexural strength. Under biaxial stress conditions, hybrid-reinforced UHPFRC including t3 and t6 fibers exhibits superior flexural strength and toughness relative to specimens reinforced with straight fibers or h fibers. UHPFRC panels typically exceed beams in normalized deflection capacity, micro crack formation, and flexural strength.

**Conclusions**

The study analyzes hybrid fiber studies in high-strength concrete since 2021. This paper highlights the increased interest in optimizing concrete mechanical properties through fiber combinations and the most significant conclusions:

1. High-strength concrete has a compressive strength of 55 MPa or greater. It is commonly used in tall building construction due to its reduced column dimensions, which improves structural efficiency and aesthetics.
2. High strength concrete has drawbacks, including limited tensile strength and ductility. These restrictions can impact the performance and durability of concrete constructions.
3. Fibers have been added to concrete mixtures to address high-strength concrete issues. Research indicates that incorporating different fiber kinds can improve concrete characteristics and performance
4. Hybrid fibers may improve high-strength concrete's tensile strength, ductility, and durability. This may result in more resilient structures that can better tolerate environmental loads.

The article suggests more research is needed to completely understand how different fibers affect high-strength concrete. This could lead to creative building and engineering applications.

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