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A REVIEW ON HYBRID FIBER-REINFORCED CONCRETE: COMBINING DIFFERENT FIBERS FOR IMPROVED STRUCTURAL PERFORMANCE

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ABSTRACT

Hybrid Fiber-Reinforced Concrete (HFRC) has emerged as a new material that addresses the limits of traditional and single-fiber-reinforced concrete. By using a mix of fibers with different properties, such as steel, synthetic, glass, and natural fibers, HFRC improves strength, ductility, crack resistance, and durability. This review summarizes recent advancements in HFRC. It highlights the combined effects of multiple fibers under various loading conditions and their role in improving mechanical performance and durability. The review also discusses challenges like fiber distribution, optimizing mix design, and cost issues. The paper ends by emphasizing the potential of HFRC for sustainable building and its promise for broad structural use.

Keywords: *Recycled aggregate concrete; mechanical properties; durability; environmental impact; sustainable construction*

1. INTRODUCTION

Concrete has been the major constituent of modern construction for ages, for it has high compressive strength; is flexible in use and cost effective. Yet, it also has limitations in terms of brittleness and low tensile and crack-control characteristics that may limit its durability and performance under service conditions. In order to counteract these deficiencies, the introduction of fibres in cementitious matrices -thus obtaining what is referred to as fibre reinforced concrete (FRC) – has been more and more developed. As received fibres such as steel, glass, synthetic polymer (e.g. Polypropylene, PVA) and natural fibres have been used separately to enhance the tensile strength, ductility and crack resistance of concrete as well as it is intended to increase the durability of concrete (Su et al., 2021). Nevertheless, the single-type fibre-reinforced concrete is still inherently limited by its own benefits. An example of this are additions of a single fibre type that may improve either one performance (e.g. crack bridging) but reduce either workability, cost or some other aspect of its long-term durability. Additionally, various loading conditions: flexure, impact, fatigue, and environmental degradation request a fibre type that could not be efficient enough. In this respect, the use of hybrid fibre-reinforced concrete (HFRC)—in which two or more types of fibres with different properties are used together—has been considered as a promising alternative (Vairagade et al., 2023). The idea behind HFRC is that fibers work in a complementary or synergistic way. For example, ductile synthetic or natural fibers prevent microcracks and enhance deformation capacity or toughness, while stiff steel fibers prevent macrocracks. As evidenced by existing studies, the functional integration of macro- and micro-fibres composed of different materials, various lengths/shapes, and different functions leads to better mechanical performances than single-fibre systems. The current experimental work by Sriram & Sidhaarth (2021) found that a hybrid combination of steel and synthetic fibres increased compressive strength by ~40% and flexural/tensile performance significantly over control and single-fibre mixes. Over the last several years, studies of HFRC have gained traction, with a growing emphasis not only on mechanical properties (compressive, tensile, flexural strength, modulus, toughness), but also on durability—the resistance to cracking, spalling, freeze-thaw, impact loads, high-temperature exposure and other environmental factors. In one such review of FRC composites it was stated that performance and longevity are influenced by the fibre-matrix interfacial bond, fibre dispersion, orientation and volume fraction (da Silva Neto et al., 2025). A more recent review that used HFRC in the title also recognises mechanisms for crack resistance, workability-related aspects, microstructures-interaction aspects and gaps related to long-term performance (Akbulut et al., 2025). However, despite these positive trends, the full utilization of HFRC for structural applications are still limited by some challenges. The uniform distribution and orientation of fibres in the concrete matrix is one of the major challenges which is not new; it is known that fibre clustering, segregation, weak bonding or non-uniform orientation will reduce the increase in performance expected. The ideal mix design (i.e. fibre types, lengths, shapes, volume fractions, matrix composition) is heavily sensitive to the particular loading and service conditions and the strength, ductility, workability and cost trade-offs are frequently non-linear. Cost represents another serious issue: the use of many fibre types, raises the cost of materials, the complexity of processes and may also negatively impact their fresh-state workability and finishing. The limited long-term durability data (e.g. under cyclic loading, extreme environments) for HFRC mixes has also been identified in several studies (Akbulut et al., 2025). HFRC also provides additional benefits to help fulfill sustainability promise in the built environment. The durability afforded by HFRC, specifically at reducing the widths and propagation of cracks, may also relieve some maintenance, prolong service life, and ultimately result in a lower lifecycle environmental footprint of concrete structures. Hybrid combinations with natural or recycled fibres are also well in-line with sustainable construction heritage. HFRC is thus a significant enabler of infrastructure that is more durable and sustainable (Alberti et al., 2024). Thus, the objective of this review is to summarise the recent advancement in HFRC, especially how the different combinations of fibres with different loading characters (steel, synthetic, glass, and natural) can positively affect the mechanical performance and durability of HFRC. It will also address the major impediments—fibre distribution, mix-design optimisation and cost problems—followed by a debate whether HFRC can be sustainable structural material or not. This will serve to demonstrate both the contemporary state-of-the-art, as well as gaps in research that need to be filled to facilitate widespread structural use of HFRC. In the following sections, the theoretical mechanisms through which hybrid fibres are expected to improve concrete performance, have been outlined, before providing an overview of the experimental evidence on both mechanical and durability performance, followed by a discussion of practical aspects and future directions for research.

2. HYBRID FIBER-REINFORCED CONCRETE (HFRC): OVERVIEW

The name Hybrid Fiber-Reinforced Concrete (HFRC) is used to characterize a concrete composite with two or more different fibres in the matrix that should be added together, commonly to improve the mechanical performance of composite compared with those for single fibre reinforcing (Dziomdziora & Smarzewski, 2025).In HFRC, the fibres employed do not have any functional differences from one another but when mixed together to form a composite the performance is better than those of individual fibres performing individually; this phenomena is referred to synergy effect which comes from fibre hybridization (Banthia & Gupta, 2004).In simple term, HFRC is a concrete (or mortar) matrix wherein two or more kinds of discrete, randomly dispersed fibers are introduced so that the combined action of the fibre system improves tensile strength, ductility, crack-control and durability in comparison to plain concrete or single-fiber reinforced concrete (Li & Deng, 2021).The hybrid arrangement is chosen such that one fibre type controls micro-cracking while another manages macro-crack propagation, hence enhancing the composite's post-crack residual strength and energy absorption capacity(Vairagade et al., 2023).

2.1 Types of Fibres Commonly Used

The choice of fiber types in HFRC broadly spans four major categories: steel fibers, synthetic fibers, glass fibers and natural fibers.

Steel fibers**:** Used to offer crack bridging and improve tensile/ductile performance, steel fibres are metallic, high-modulus, high-strength (usually stainless or carbon steel) fibres (Zhong et al, 2021).
Synthetic fibres**:** Polymers such as polypropylene, polyvinyl alcohol (PVA), polyethylene (PE) and similar, which are non-metallic, corrosion-ressistant and primarily help control plastic early age shrinkage cracks and enhance ductility (Mehrabi et al., 2024).
Glass fibres: Particularly in uses when corrosion or electromagnetic neutrality matter, alkali-resistant glass (AR-glass) fibres give reinforcement and help to control cracks and extend durability (Ahmad & Awang, 2013).
Natural fibres**:** Rising as environmentally friendly substitutes are fibers from renewable sources (such as jute, hemp, sisal, coir). Though they are usually less strong and modulus than steel or synthetic fibres, they provide environmental advantages and could help with crack management and ductility (Geremew et al, 2025).

2.2 Mechanisms of Hybrid Action

In order to take advantage of the strengths of various fibres used in concrete, they can be combined. Doing so, hybrid fibres have been proved more economical and better than fiber individual performance (Selvan et al., 2024). Achieving these improvements from fibre systems is primarily due to several mechanisms:
Micro-crack control**:** Short or low modulus fibres (e.g. from synthetic and natural sources) restrict the initiation and growth of micro-cracks under load or shrinkage. These fibres improve the stress redistribution early in cracking (Akbulut et al., 2025).
Macro-crack bridging and arresting**:** Longer, higher-modulus fibres (such as steel) act to bridge larger cracks, transfer tensile stresses across crack planes, delay crack propagation and improve post-cracking residual strength and toughness (Gali et al., 2017). The introduction of fibers of different lengths promotes the creation of a continuous reinforcement network in concrete. Microfibers limit

the development of microcracks, whereas macrofibers are responsible for controlling the formation and development of larger cracks (shown in Figure 1).

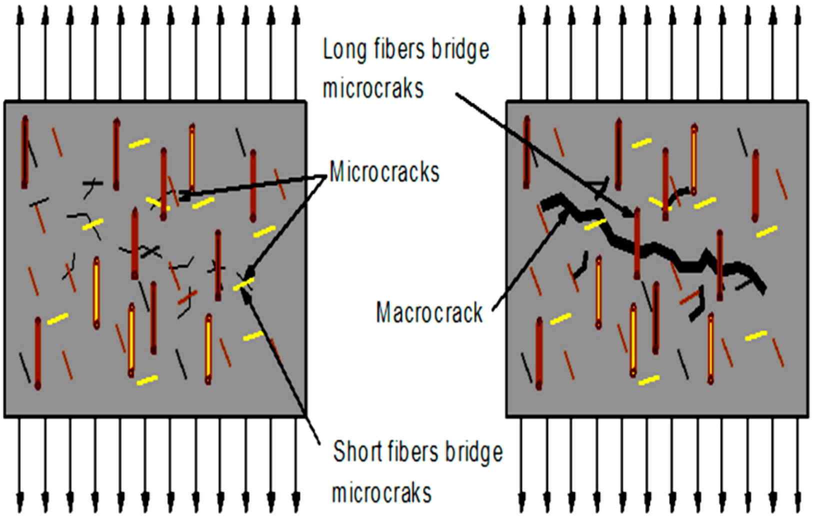


Figure 1: Schematic illustration of micro- and macrocrack bridging in UHPC by hybrid fibers (Dziomdziora & Smarzewski, 2025).

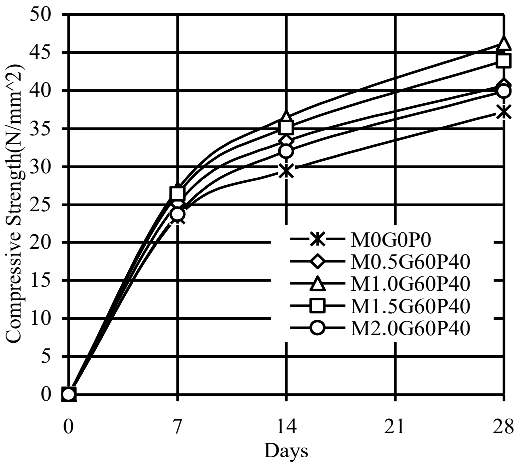
Synergistic interaction: With the right choice of fibres, the aggregate performance of hybrid systems can exceed that which would be expected from each fibre separately. For example, in one study, the coefficient of hybridization effect in some steel-fiber combinations even surpassed unity, revealing a synergy (He et al., 2022).

Improved energy absorption and ductility**:** Because it combines fibre types with different mechanical properties (modulus, aspect ratios, bond characteristics), HFRC has both higher resistance to fatigue and superior hardness even under impact load (Dziomdziora & Smarzewski, 2025).

3. MECHANICAL PERFORMANCE AND DURABILITY CHARACTERISTICS

Hybrid Fiber-Reinforced Concrete (HFRC) includes compressive, tensile, and flexural behaviour among its mechanical performance, enhanced crack resistance and ductility, and the synergistic effects stemming from many fibre compositions. HFRC shows superior compressive strength than plain or single-fibre reinforced concrete. One study, for instance, found that a hybrid of low-modulus and high-modulus fibres improved compressive strength by up to approximately 15–40% compared to the control concrete (Dziomdziora & Smarzewski, 2025). The Figure 2 shows the increase the compressive strength as the fiber volume increases. However, when the total fiber volume is increased more than 1% the reduced in strength was observed. The Mix M1.0G60P40 showed an increase in strength about 24.2% than the controlled mix. The compressive strength of M1.5G60P40 mix decreased gradually about 5.2% compared to the mix M1.0G60P40 where the total fiber volume is kept as 0%, 0.5%, 1.0%, 1.5% and 2% of cement weight. For each mix in the total volume of fiber 60% of it is glass fiber and 40% is polypropylene fiber (Grace et al., 2020). Typically even more noticeable are improvements in tensile (splitting) and flexural strength: in the same study, for example, the splitting tensile strength rose by 12% and 26% respectively across two mixes (Dziomdziora & Smarzewski, 2025). Grace et al.(2020) shows that the splitting tensile strength of M1.5G60P40 mix decreased gradually about 13.4% compared to the mix M1.0G60P40(Figure 3). Furthermore, HFRC's stress-strain curves show better post-peak behaviour and greater peak strains than regular concrete, hence pointing to enhanced ductility (Abdulhameed et al., 2022). Higher ultimate loads, lower deflection under service load, and better residual load carrying capability following cracking have all been demonstrated in flexural performance tests (e.g., beam tests)(Lakavath et al., 2022). Improved crack resistance and ductility are among the main benefits of HFRC.

Multi-scale crack management is made possible by the presence of fibres with different moduli, lengths and bonding properties.



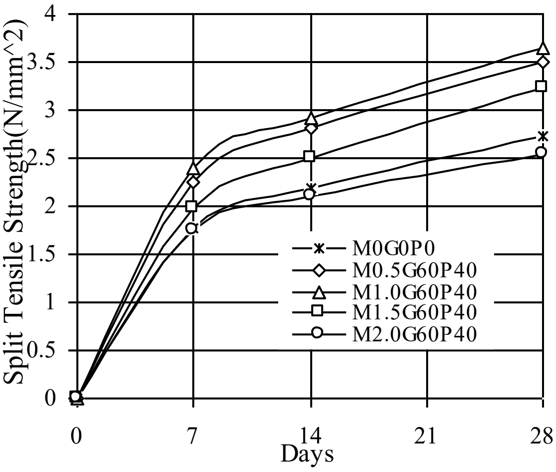


Figure 2: Compressive strength of different fibers variations (Grace et al, 2020).

Figure 3: Split Tensile strength of different fibers variations (Grace et al., 2020).

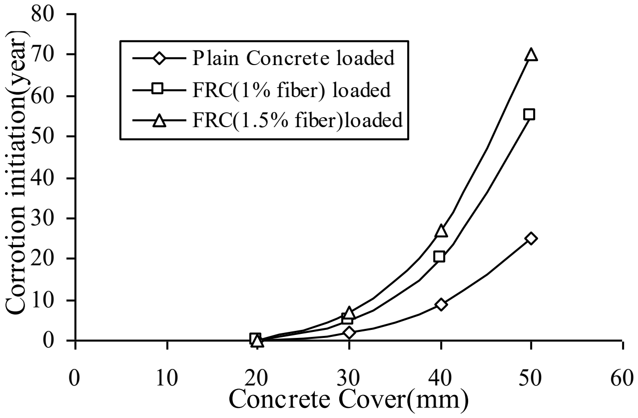


Figure 4: Predicted corrosion initiation of FRC and plain concrete at varying cover depth (Paul et al., 2020)

Longer, stiffer fibres bridge macro-cracks; shorter, more flexible fibres control microcracks. For instance, Vairagade et al. (2023) notes that hybrid systems improve toughness, energy absorption, ductility and lower fracture spacing as opposed to mono-fibre systems. One fibre type restricts crack initiation; the other slows crack propagation and widening. Moreover noted is the enhanced post-cracking deformability (ductility): HFRC exhibits a more steady load decline following peak and maintains leftover strength for greater deformations (Grace et al., 2020). For instance, Dziomdziora & Smarzewski (2025) demonstrates that combining low-modulus fibres (which enhance workability, early crack control) with high-modulus fibres (which boost strength and stiffness) produces optimized properties. One main finding was that higher mechanical performance was reached by a hybrid mix at a given total fibre volume than by either fibre alone, suggesting greater than additive effect, hence synergistic action. The actual result is that mix design should maximise fibre types, lengths, moduli, and volume ratios so as to take advantage of synergy rather than just add up results (Vairagade et al, 2023). Durability of HFRC includes permeability and crack control, and resistance to fatigue, corrosion, freeze–thaw cycles and chemical attack. Permeability and crack control are thus the main issues. Crack control is the core of lasting: more severely controlled crack widths reduce penetration by deleterious agents (chlorides, sulfates, freeze water) and so increase service life. HFRC, with its improved crack bridging and slow crack propagation, demonstrates better durability. For example, one review of fiber–reinforced concrete durability stated that fiber reinforcement reduces crack width, slows crack propagation, and improves permeability (Paul et al., 2020). Elhawary et al. (2022) used 1 % steel + 0.3 % polypropylene fibres and found better compressive strength still after 120 days of aggressive media treatment and over 360 days in total, showing reduced permeability and better crack control. The hybrid fiber systems have better performance under alternating environmental load conditions. Under chloride, sulfate or water environments HFRC retained higher compressive, tensile and flexural strengths than normal concrete. Corrosion resistance is enhanced indirectly by cracking wide and internal crack bridging, which keeps aggressive agents from entering the material. Paul et al. (2020) found that the benefit of FRC over RC under unloading condition is not obvious as the difference in results was insignificant. However, under the same loading condition (bending load), time to corrosion initiation in FRC was prolonged about 2.2 to 3.6 times; varying with the fiber content and cover thickness (Figure 4). A broader review on effects of fibers on fatigue, freeze-thaw and chemical resistance was cited: fiber reinforced concretes deform less rapidly, crack more slowly and have a higher residual strength than plain concrete. Moreover, in another hybrid fibre study it was found that dynamic loads (impact/fatigue) can also be resisted better by the ultimate fiber systems (Elhawary et al., 2022). Table 1 shows the summary of hybrid fibers used and performance improvement.

Table 1: Hybrid fibers used and respective results as per different studies

References	Fiber used	Performance Improvement
(Hou et al., 1997)	Glass and PP	Ageing led to a rise in the flexural peak load of hybrid sheets.
(Itaru et al., 2000)	Short and long steel	HFRC has a lower permeability than regular concrete
(Banthia et al., 1990)	Steel and carbon	More steel fibres in hybrids result in a more noticeable increase in strength. More fibres result in a further significant rise in toughness.
(Hua et al., 2000)	Polypropylene and Carbon	Using hybrid versions of carbon and PP fibre, concrete's fatigue characteristics were enhanced.
(Qi et al., 2000)	Polypropylene and Carbon	The hybrid fibres, which could remove the crack origins and prevent the fracture from spreading, were what gave the carbon-PP HFRC its added strength and toughness.
(Stroeven et al., 2001)	Steel, Carbon, PP	Combining steel and carbon fibres resulted in a greater material toughness.
(Soroushian et al., 1993)	Polypropylene fiber and Polyethylene pulp	Hybrids improved flexural strength and toughness and were helpful in impact loading.
(Nam-Wook et a1., 2000)	Steel and PP	When compared to mono fibre composites, hybrid fibre reinforced concrete's resistance to the initial crack's commencement and hardness were significantly increased.
(Feldman & Zheng, 1993)	Steel and PP	In the HFRC, the stiffer, stronger steel fibres increased ultimate strength while the ductile, flexible polypropylene fibres increased strain capacity and toughness in the post crack zone.

4. APPLICATIONS AND SUSTAINABILITY PERSPECTIVE

HFRC has demonstrated good potential in marine and coastal buildings, since hybrid fibre (e.g. steel and polymer or glass) provides better crack management and chloride ingress resistance which is critical in severe saline conditions. The ability to increase ductility and crack-control behaviour in high-rise buildings can enable the hybrid fibre combinations to add to load-bearing capacity, dynamic load energy absorption, and seismic resilience. Hybrid FRC is also ideal in the application of pavements and airport runways where loads tend to be repeated and load cycles and impact toughness, fatigue resistance and post-crack resistance is required which hybrid fibres provide (Akbulut et al., 2025). In tunnels, beam, and precast concrete panels, HFRC is strengthened in flexural strength, residual load carrying capacity, and under bending by synergistic macro- and micro-fibre action. The hybrid fibre in the concrete prolongs the life of the concrete because of its enhanced durability (resisting cracking, freeze-thaw cycles, and corrosion), thus necessitating less repair and replacement, and the environmental impact of a structure throughout its lifetime (Dziomdziora & Smarzewski, 2025).

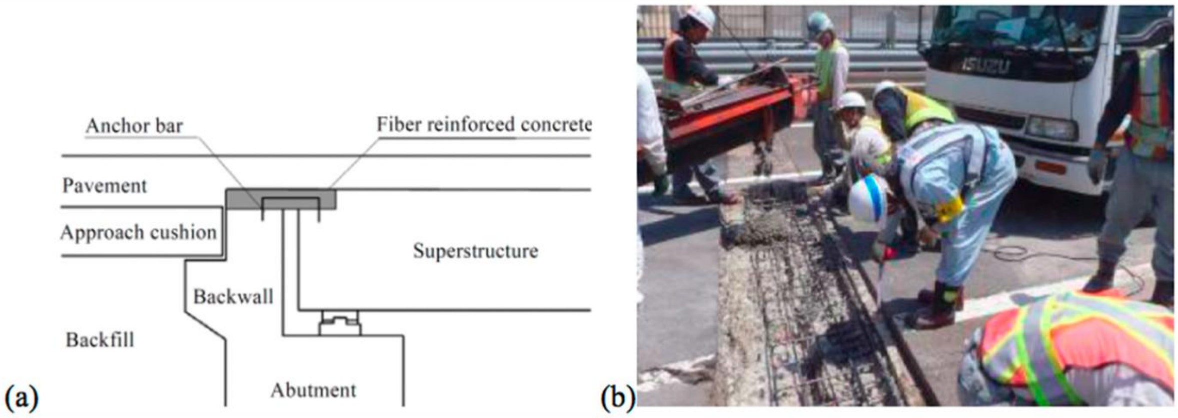


Figure 5: Schematic of an (**a**) FRC abutment-slab connection to prevent leakage and corrosion in highway infrastructure, and (**b**) casting of the FRC (Ishikawa et al., 2014).

Other hybrid fibre concrete recipes incorporate polymer fibres that are recycled (e.g. used as a bottleneck in PET bottles) and natural fibres such as jute, leading to waste reduction and enhanced mechanical performance and sustainability. HFRC Life Cycle Assessment (LCA) of HFRC reveals that a small content of fibre (e.g. 1 per cent) could dramatically increase the durability but with a relatively low environmental penalty, thereby enhancing the life-cycle environmental performance of the concrete (Paul et al., 2020).Hybrid fibre is used to make the crack widths diminish and in this way, makes permeability and ingress of harmful agents minimal; this decreases the maintenance, making HFRC a resource efficient method of construction. Natural fibres of plants (e.g. flax, jute) in HFRC contributes to a strategy of bio-based and low-carbon material, as these fibres store carbon in the growing process and eliminate the use of entirely synthetic fibres or steel fibres. Resilience and sustainability HFRC has a higher fatigue resistance, and since it has a lower rate of repair, it is more resilient to extreme loads (impact, cyclic) and offers a more durable infrastructure, which leads to sustainable long-term performance (Khaleel et al., 2025).

5. CHALLENGES AND LIMITATIONS

Non-uniform fiber dispersion is one of the primary challenges of HFRC, and in hybrid mixtures (different kinds, shapes, sizes, and densities of the fibers), fiber clumping, balling, or segregation during the mixing process are common, and this leads to weak regions and non-uniform strengthening (He et al., 2022). Distribution of varied fiber geometries and densities is a challenge: coarse steel fibers tend to sink or still interlace with the lighter natural or synthetic fibers, therefore reducing their efficacy (Akbulut et al., 2025). Since it is difficult to confirm consistency in a full-scale element, bad dispersion also makes quality control challenging: uneven reinforcement will impair structural integrity. The other significant constraint is mix optimization: HFRC design space is large as one must select not only the type and quantity of fibres but also aspect ratios, ratios, and interactions between the fibre and the cementitious macrostructure, creating time and resource-intensive trade-offs between fresh-state workability and hardening properties (He et al., 2022).These issues make finding the optimum balance a time-consuming and resource-intensive process that does not allow realistic acceptance. Moreover, the behaviour of hybrid fibre systems in terms of long-term shrinkage, cracking, durability, and strength are not necessarily linear and predictable; interactions (e.g., bond strength, pull-out behaviour) between the fibers and the matrix should be controlled. Regarding economic perspectives, HFRC generally implies the increased cost of material: specialty fibres (steel, carbon, synthetic or treated natural fibers) are more expensive than traditional concrete products, thus mixed hybrid mixes require more careful treatment. In addition to that, gouging up the cost of mixing, laying, and quality assurance is that closer attention has to be paid to fiber dispersion and the possibility of using additional admixtures (e.g., superplasticizers) to offset the higher initial cost, particularly with basic applications where conventional concrete or cheaper reinforcement is already doing a fine job (Khaleel et al., 2025).The performance benefits (e.g., increased toughness, reduced crack widths) may not necessarily justify the higher initial cost, particularly in basic applications where more cost-effective concrete Lastly, the lack of unified design and specification of HFRC increases financial risk: contractors and owners may hesitate to consider using hybrid fiber systems due to uncertainty about performance, cost-benefit, and long-term maintenance(Akbulut et al., 2025).

6. CONCLUSIONS

Providing a useful solution to the inherent limitations of traditional and single-fiber-reinforced concrete, Hybrid Fiber-Reinforced Concrete (HFRC) has become a significant breakthrough of cementitious composites. The complimentary mechanical contributions of different types of fibers such as steel, synthetic, glass, and natural fibers are combined and used by HFRC. This hybrid behavior makes superior increases in tensile strength, fracture bridging, post-cracking ductility, impact resistance, and overall structural resilience possible. According to the literature, HFRC also exhibits superior performance using the composite of the micro-fibers governing first-hand micro-fine cracks and macro-fibers resisting broader cracks in the latter phases of loading. Its ability to control the crack width leads to better fatigue life, reduced sensitivity to the corrosion and chemical assault process, increased freeze thaw and reduced permeability. Despite all these benefits, HFRC is not without predicaments because industrial floors, tunnel linings, bridges, overlays, and roads which require long life span and minimum maintenance are some of the areas where HFRC can be applied. The consistent fiber distribution, maximization of mix design, control of workability, and addressing of the cost constraints still hinder the widespread acceptance. Hybrid mixtures will require accurate ratios, appropriate methods of mixing and improved quality management procedures to ensure consistent performance. There are also economic factors that influence practical implementation, such as specialty fiber costs and additional admixtures. Also contributing to the variability of the outcomes and indecision of engineers and practitioners is the absence of standardized norms in design, testing, and proportions. Nevertheless, the HFRC as a high-performance, sustainable and effective substance remains quite promising. With the help of their improved structural performance, hybrid fiber mixes can reduce overall material use and reduce the reliance on traditional steel reinforcement. Furthermore, recycled or natural fibers will enhance the sustainability of the environment and promote the idea of the circular economy within the building sector. Further research on fiber synergy, optimization of mix, long term durability, economical formulations will help in bridging the existing gaps and accelerate mainstream structural implementation of fiber. HFRC can be a very useful, reliable, and eco-friendly material to use in future infrastructure projects provided that it is properly standardized, quality-monitored, and developed with reasonable methods.

DECLARATION OF USE OF AI

This paper a comprehensive review on application of Hybrid fiber reinforced concrete encompassing unique summary of prevalent literatures by the authors. The authors acknowledge use of online AI tools along with Google Scholar to search for relevant papers. Authors have not use any AI tools to prepare this manuscript.

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