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(REVIEW ARTICLE)

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A review on mechanical toughness and durability of hybrid steel polyester fiber reinforced concrete

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Abstract

This paper presents a comprehensive review of Hybrid Fiber Reinforced Concrete (HFRC), which combines different fibers, such as steel, polyester, polypropylene, and glass, to enhance the mechanical properties and durability of concrete. Recent studies highlight the synergistic effects of hybrid fibers in improving compressive strength, flexural strength, tensile strength, and crack resistance compared to single-fiber concrete systems. Hybrid fiber incorporation also significantly enhances durability parameters, including freeze-thaw resistance, water absorption, and corrosion resistance, making HFRC suitable for use in high-performance applications like seismic-resistant structures, pavements, and industrial floors. Various experimental studies have shown that the combination of steel and polyester fibers provides superior energy absorption, ductility, and impact resistance, while also improving the microstructure and reducing porosity. Additionally, finite element modeling has confirmed the improved flexural toughness and overall performance of HFRC under dynamic and cyclic loading conditions. The paper also explores future research directions, including the optimization of fiber content and type to enhance the sustainability and cost-effectiveness of hybrid fiber concrete. The review emphasizes the importance of fiber interaction, optimal fiber ratios, and environmental exposure conditions in maximizing the potential of HFRC for modern infrastructure projects.

Keywords: Hybrid Fiber Reinforced Concrete; Steel Fiber; Polyester Fiber; Durability; Mechanical Strength; Crack Resistance; Flexural Strength; Sustainability.

1. Introduction

Concrete remains the most widely used human-made construction material, with global output estimated at about 14.0 billion m^3 in 2020, while global cement production was about 4.2 billion tonnes in the same year. The scale of this consumption explains why improvements in toughness, crack resistance, service life, and durability have become central research priorities in modern concrete technology. The cement and concrete sector is also under increasing pressure to improve material efficiency because it is responsible for roughly 7% of global CO_2 emissions, making durability-oriented design not only a structural issue but also a sustainability imperative. Recent industry and policy assessments further note that total CO_2 emissions from cement and concrete remain above 2015 levels, even though decarbonization pathways now strongly emphasize longer service life, reduced maintenance frequency, lower repair demand, and improved life-cycle performance. In parallel, the global steel industry reported crude steel production of about 1,882 million tonnes in 2024, underlining the continuing availability of steel-based reinforcement products for high-performance composites. Against this global backdrop, fiber-reinforced concrete has attracted major attention because ordinary concrete, despite its high compressive strength, remains brittle in tension, vulnerable to shrinkage cracking, and susceptible to progressive damage under impact, fatigue, thermal gradients, and aggressive exposure. The review topic of hybrid steel–polyester fiber reinforced concrete emerges from this engineering need: to create a

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cementitious composite that is not only strong, but also damage-tolerant, crack-arresting, and durable enough for pavements, bridges, industrial floors, marine structures, precast elements, tunnels, and seismic applications.

The technical basis for using steel fibers in concrete is well established. Steel fibers improve post-cracking resistance by bridging macrocracks, redistributing tensile stresses, delaying unstable crack growth, and increasing fracture energy, flexural toughness, residual load-carrying capacity, and impact performance. A 2024 systematic review reported that an optimal steel fiber volume fraction of about 0.5–2.5% can increase compressive strength by roughly 8–12%, splitting tensile strength by 15–45%, and flexural strength by 10–40%, although excessive dosage may reduce workability because of balling, poor dispersion, and increased internal friction. Another 2023 review on fracture properties showed that crack resistance and fracture performance rise significantly as steel fiber volume fraction increases from 0 to about 1.6%, highlighting the strong relationship between fiber dosage and energy absorption capacity. These findings are highly relevant to the present topic because toughness is not governed only by peak strength; it is more fundamentally governed by the ability of a composite to absorb energy after matrix cracking. In structural terms, steel fibers are especially valuable under dynamic, repeated, or localized loading where conventional concrete tends to fail in a sudden and brittle manner. Yet steel fibers alone do not solve every problem. High steel-fiber contents can reduce slump, complicate placement, and create non-uniform fiber orientation. In aggressive environments, the possibility of corrosion at exposed fiber ends or near cracked surfaces also remains a design concern. Therefore, current research increasingly favors hybridization strategies, where a second fiber type is added to control early-age and micro-level cracking while steel fibers continue to resist macro-level fracture and post-crack deformation.

Within this hybrid concept, polyester fibers are technically important because they act at a different scale from steel fibers. Polyester fibers, being lighter, finer, non-corrosive, and chemically stable in many service conditions, are particularly effective in reducing plastic shrinkage cracking, restraining microcrack initiation, controlling crack width, lowering permeability pathways, and improving resistance to surface deterioration. Their contribution is often less dramatic in terms of absolute compressive strength than that of steel fibers, but they are highly influential in durability-related behavior because the durability of concrete is governed largely by the formation, connectivity, and propagation of cracks. Research on synthetic fibers has consistently shown that optimum dosage is critical: moderate additions can enhance tensile behavior, abrasion resistance, and spalling resistance, whereas excessive fiber content can reduce workability and create entrapped voids that negate performance gains. A 2023 study on polyester-containing reactive powder concrete reported that a 0.5% fiber dosage delivered superior residual mechanical and durability performance at elevated temperatures, while lower contents around 0.1% were effective in improving spalling resistance. This is significant because thermal stability, crack control, and residual strength after heating are major concerns in tunnels, industrial facilities, and fire-exposed infrastructure. When polyester fibers are combined with steel fibers, the hybrid system becomes multi-scale: polyester fibers limit the birth and coalescence of microcracks, while steel fibers bridge wider cracks and sustain load transfer after cracking. The result is a tougher and more damage-tolerant composite than mono-fiber concrete. This multiscale crack-control mechanism is the principal scientific reason why hybrid steel–polyester fiber reinforced concrete is being studied as a superior alternative to plain concrete and even to single-fiber systems for long-life structural applications.

From a review perspective, the mechanical toughness and durability of hybrid steel–polyester fiber reinforced concrete must be understood as interrelated rather than separate properties. Toughness improvement reduces crack opening and slows damage localization, while durability improvement reduces the ingress of chlorides, sulfates, moisture, and other aggressive agents that accelerate reinforcement corrosion, freeze–thaw distress, abrasion, and long-term strength loss. This coupling is central to present-day concrete engineering, especially as the global construction sector seeks materials that deliver higher performance with lower life-cycle environmental cost. Industry data show that the global concrete fibers market was valued at about USD 2.3 billion in 2024 and is expected to grow strongly through the next decade, reflecting the expanding demand for fiber-enhanced materials in infrastructure and industrial construction. The steel fiber market itself was valued at about USD 2.44 billion in 2024, again indicating the commercial relevance of fiber-based reinforcement systems. For the present review topic, this worldwide trend supports the need for a technically rigorous synthesis of how hybrid steel and polyester fibers influence compressive strength, split tensile strength, flexural behavior, toughness indices, impact resistance, shrinkage control, permeability, water absorption, abrasion resistance, thermal performance, and resistance under chemical or marine exposure. A proper review paper introduction must therefore position hybrid steel–polyester fiber reinforced concrete not as a niche mix modification, but as an evolving high-performance composite aligned with global needs for resilient, durable, and sustainable construction. In that sense, the topic is timely, scientifically relevant, and practically important because it directly addresses the fundamental weakness of ordinary concrete—its brittleness—while also responding to the worldwide demand for longer-lasting infrastructure with lower repair frequency and better life-cycle efficiency.

2. Deterioration processes affecting fiber reinforced concrete

In general, the deterioration of concrete can be caused by a variety of physical, chemical, or mechanical processes, often acting in combination. One of the most common deterioration mechanisms affecting reinforced concrete infrastructures is the corrosion of steel reinforcement. Corrosion is an electrochemical process in which the flow of charges (electrons and ions) occurs between the anode and cathode. Under normal conditions, a passive film forms spontaneously on the steel surface due to the alkaline environment created by the hydration of concrete, which protects the steel from corrosion. However, this passive layer can break down due to chloride ingress or carbonation, leading to active corrosion. Chloride ingress (via deicing salts, seawater, etc.) and carbonation (the reaction of CO_2 with calcium hydroxide in concrete) are two main causes that break down the passive film on steel reinforcement, thereby allowing active corrosion to occur. Additionally, cracks in the concrete structure significantly accelerate the corrosion process, both in the initiation and propagation periods. The cracking process in fiber-reinforced concrete (FRC) differs from that in plain concrete, and thus, it is reasonable to expect that the deterioration processes, such as corrosion, may also behave differently.

Table 1 Overview of the Influence of Cracks in Fiber Reinforced Concrete on Corrosion of Reinforcing Steel

Reference	Fiber Type/Content	Exposure Time (months)	Crack Width (mm)	Carbonation Depth (mm)	Total Chloride Content (%)	Corrosion Damage
Vasanelli et al. (2021)	Steel, 0.6%	17	Wcr, ave 0.13	15.11–16	–	–
	Polyester fibers, 0.9%	17	Wcr, ave 0.13–0.16	14.87–17.47	–	–
Kobayashi & Kojima (2020)	Polypropylene, 1.5%	11	Wcr, tot 0.04–0.26	0.38–0.63	Mass loss, 5%	–
	Polypropylene, 1.0%	11	Wcr, tot 0.02–0.12	0.55–0.62	Mass loss, 8%	–
	Polypropylene, 0.75%	11	Wcr, tot 0.04–0.08	0.55–0.60	Mass loss, 10%	–
Miyazato & Hiraishi (2021)	Polyethylene, 1.5%	3	Wcr, ave < 0.1	21.6 (w/c=0.3)	28.8 (w/c=0.6)	–
Micelli et al. (2020)	Steel, 0.6%	72	Wcr, ave 0.19	39	–	–
	Polyester fibers, 0.9%	72	Wcr, ave 0.16	37	–	–
Chen et al. (2022)	Steel, 0.5%	36	Wcr, ave 0.10–0.40	–	–	Pitting area, ~17%
	Polyvinyl alcohol, 0.75%	36	Wcr, ave 0.10–0.40	–	–	Pitting area

The influence of fibers on corrosion in cracked concrete has been a subject of several studies. The presence of fibers, particularly steel, polyester, and polypropylene fibers, can alter the crack width and depth of carbonation, which ultimately affects the corrosion damage. To understand this better, Table 2 presents an overview of various studies that explore the influence of fibers on the corrosion of steel reinforcement in cracked concrete. These studies provide insights into how different fibers can influence crack widths, carbonation depth, chloride content, and corrosion damage. This table provides a general overview of several studies that have explored the influence of different fibers on the corrosion behavior of steel reinforcement in cracked fiber-reinforced concrete. The studies listed focus on various fiber types, their content, and the effects they have on corrosion damage, crack widths, chloride content, and carbonation depth. As observed, steel fibers generally show a higher carbonation depth and corrosion damage due to their greater ability to form cracks under stress. However, fibers such as polypropylene and polyester reduce the extent of cracking and hence the potential for corrosion initiation. This comparison highlights the necessity to balance fiber content and type in FRC to optimize its mechanical performance and durability. Further studies are required to explore the long-term impact of fiber types on corrosion, especially in regions with high environmental exposure such as marine environments or areas with high chloride presence.

3. Research method

The research methodology employed in this study involves a comprehensive systematic review of literature related to Hybrid Steel-Polyester Fiber Reinforced Concrete (HyFRC), focusing on its mechanical toughness and durability. A total of 150 research papers were initially identified through database searches, followed by strict screening criteria based on relevance, publication year, and experimental validity. After the screening, data extraction was performed to gather information on fiber types, content, testing methods, and performance indicators. Papers were assessed for eligibility, and high-quality studies were selected, providing a robust basis for synthesizing findings and identifying trends, gaps, and future research directions in the field.

3.1. Literature Review Approach and Initial Paper Selection

The research began by gathering 150 papers related to Hybrid Steel-Polyester Fiber Reinforced Concrete (HyFRC), focusing on its mechanical toughness and durability. A comprehensive search was conducted across multiple databases, including Google Scholar, ScienceDirect, SpringerLink, and Wiley Online Library. The selection was based on specific keywords like "fiber reinforced concrete", "hybrid fiber concrete", "steel polyester fiber", "corrosion resistance", and "durability of concrete".

Figure 1 Research Method

The initial search resulted in a pool of 150 papers, which were further screened to ensure relevance to the research topic. The inclusion criteria were as follows:

- Peer-reviewed journal articles, conference papers, and dissertations.
- Papers published from 2010 to 2025, ensuring recent developments.
- Studies focusing on mechanical properties, corrosion resistance, and durability of HyFRC.
- Experimental, analytical, and numerical modeling studies related to the topic.

Papers were excluded if they did not focus on fiber-reinforced concrete or did not contain relevant data on toughness, corrosion, or durability properties. The result was 130 eligible papers that met the inclusion criteria.

3.2. Paper Screening, Cleaning, and Data Extraction

Following the paper selection, a screening and data extraction process was implemented to ensure consistency and reliability. Data cleaning was performed to remove irrelevant or duplicated studies. The selected papers were analyzed for key variables like:

- Fiber Type (e.g., Steel, Polyester, Polypropylene).
- Fiber Content (percentage by weight).
- Test Methods (e.g., Flexural Strength, Tensile Strength, Corrosion Resistance).
- Exposure Conditions (e.g., chloride attack, carbonation depth, freeze-thaw cycles).
- Performance Indicators such as compressive strength, crack resistance, energy absorption, and pitting area.

The extraction process ensured that only experimental data related to HyFRC's mechanical toughness and long-term durability were recorded. Information was extracted into a spreadsheet format to categorize data on:

- Crack width (Wcr): Average and total crack width.
- Carbonation depth: Depth of CO_2 penetration affecting the reinforcement.
- Chloride content: Influence on corrosion initiation.
- Corrosion damage: Mass loss, pitting area, or corrosion propagation.

Through this process, 100 papers were retained for the review, focusing specifically on experimental work that provides measurable and consistent data on HyFRC's performance under various loading and environmental conditions.

3.3. Data Synthesis and Analysis

After cleaning and screening the papers, the next step involved data synthesis to identify patterns, gaps, and trends in the existing literature. Studies were categorized based on:

- Fiber Type and Content: Comparison between steel and polyester fibers and their combination in HyFRC.
- Environmental Conditions: The effects of exposure to chloride, carbonation, and freeze-thaw conditions on corrosion and material degradation.
- Performance Indicators: Mechanical toughness was assessed in terms of flexural strength, residual strength, and energy absorption post-cracking. Corrosion performance was analyzed through chloride ingress, pitting corrosion, and mass loss.

The synthesis showed that steel fibers significantly improved flexural strength and crack resistance, while polyester fibers enhanced ductility and energy absorption after cracking. The combination of both fibers in HyFRC led to improved overall performance in terms of mechanical toughness and durability, particularly in preventing crack propagation and corrosion initiation. Research gaps identified include the need for long-term durability studies, particularly in severe environmental conditions, and optimum fiber combinations that balance cost-effectiveness and performance. The synthesis of data also points to the potential for using recycled fibers and eco-friendly alternatives to enhance the sustainability of HyFRC in construction.

4. Related work

One of the most comprehensive experimental studies on hybrid steel-polyester fibers was conducted by Chella Gifta Christopher et al. (2023). This research evaluated the mechanical properties and durability of Hybrid Fiber Reinforced Concrete (HyFRC) using both steel and polyester fibers in an M45 grade concrete mix enhanced with fly ash and silica fume. The results demonstrated that hybrid fiber addition significantly improved compressive strength up to 14% at a 0.5% fiber volume fraction compared to plain concrete. Moreover, the toughness under split tensile loading increased by 26–72% for hybrid fibers compared to only polyester fibers, and by 10–18% compared to only steel fibers, highlighting the synergistic effect of combined fibers on energy absorption and post-crack behavior. The study also reported improved water sorptivity and enhanced electrical conductivity, which is often correlated with crack bridging behavior in fiber composites. Continuing in 2025, R. Ashwathi et al. (2025) examined the performance of concrete with a binary blend of steel and polyester fibers, published in *Procedia Structural Integrity*. They observed that incorporating hybrid fibers improved the overall mechanical performance and crack resistance beyond what each fiber could achieve individually. In particular, steel fibers contributed to tensile strength enhancement, while polyester fibers provided improved toughness and resistance to impact loading conditions. The study emphasized the importance of selecting an optimal fiber percentage to maximize mechanical properties without compromising workability. M Kazemian et al. (2023) investigated hybrid fiber reinforced concrete mixtures focusing on achieving superior mechanical performance through optimized fiber combinations. Their work noted that diverse fiber reinforcement can greatly improve tensile strength and ductility, especially when using hybrid systems that balance the high modulus of steel fibers and the crack arresting capability of polymeric fibers. These hybrid configurations helped enhance both crack control and energy dissipation under loading. Together, these studies indicate that hybrid steel-polyester fiber combinations contribute not only to conventional concrete's mechanical enhancements but also to improved durability parameters like water transport and long-term performance. The consistent improvement in strength and toughness metrics across multiple studies confirms the efficacy of hybrid fiber reinforcement as a viable strategy for advanced concrete composites.

Beyond mechanical strength, researchers have also focused on fracture mechanics and flexural responses in fiber-reinforced composites. The study by R Ashwathi et al. (2025) further explored how hybrid fibers affect structural performance under stress. Their experimental investigation confirmed significant improvements in crack resistance, flexural behavior, and overall structural toughness when fibers were synergistically blended, compared to mono-fiber mixes. These enhancements result from the complementary action of steel fibers distributing load and polyester fibers arresting micro-crack propagation. An important comparative study within hybrid systems is observed in broader literature (e.g., hybrid steel/polypropylene work) showing hybridization improves tensile properties and toughness indexes more effectively than single-fiber systems. While not steel-polyester specific, this framework helps contextualize how combining a ductile polypropylene or polyester component with steel fibers greatly enhances crack bridging, energy absorption, and resistance to micro-cracking under tensile loading. Another notable contribution comes from research on hybrid fibers in self-compacting hybrid concrete by H Hu (2025), which highlighted improved flexural-tensile performance and reduced macro crack widths compared to plain concrete under load. The study also showed a 41.15% increase in compressive strength due to hybrid reinforcement, illustrating the potential of combined fibers for both strength and durability enhancements relevant to HyFRC applications. In 2025, studies like that of R Ashwathi et al. have reinforced the idea that integrative fiber systems not only improve individual performance metrics but also contribute to overall resilience under cyclical and impact load conditions, making hybrid fibers suitable for infrastructure subjected to dynamic stresses.

Durability remains a core focus, particularly when evaluating how hybrid fibers influence long-term performance and resistance to structural deterioration. The experimental work by Christopher et al. (2023) showed that hybrid steel-polyester fibers improved water sorptivity results, indicating reduced permeability which is important for resisting environmental degradation due to moisture and chloride ingress. Additionally, the combination of fibers enhanced post-crack energy absorption, crucial for durability under repeated loading conditions. Recent research trends highlight the role of hybrid fibers in increasing concrete resistance to freeze-thaw cycles and environmental distress, such as evidenced in broader hybrid fiber studies (e.g., hybrid steel/basalt combinations) that emphasize improved durability performance relative to single fiber mixes. These findings underline the potential benefits of extending hybrid concepts to steel-polyester systems for durability optimization. Studies also emphasize how fiber synergies can influence microstructural behavior and crack propagation patterns, which directly contribute to enhanced durability performance. By limiting the formation of wide cracks a key pathway for environmental ingress hybrid systems such as steel-polyester reinforced concretes display better long-term stability and resistance to deterioration. Finally, ongoing work in this field, including performance evaluations published in 2025, continues to support and extend these findings by quantifying how varying fiber content influences not just mechanical behaviour but also durability indicators such as shrinkage, sorptivity, and micro-crack propagation under real service conditions.

4.1. Fiber Reinforced Concrete (FRC)

Recent research on fiber reinforced concrete (FRC) emphasizes its enhanced mechanical performance, including compressive, tensile and flexural strengths, crack resistance, and durability improvements compared to plain concrete. A state-of-the-art review by Pham (2025) provides a deep understanding of how fiber stiffness influences mechanical behaviour, durability, and even eco-economic aspects of FRC. By framing fiber performance in terms of Young's modulus and bridging mechanisms, this review highlights the significant role of fiber characteristics in governing post-crack toughness and mechanical resilience. In a complementary study, Zheng et al. (2024) reviewed 137 research papers on steel fiber reinforced concrete (SFRC), summarizing fracture toughness, constitutive modelling, and crack resistance mechanisms from a microscopic viewpoint. Their findings underscore how steel fibers improve not only compressive strength but also fracture energy and durability performance under load. A focused experimental analysis by Lee (2023) evaluated the structural and functional properties of multiple fiber types (steel, glass, carbon) and demonstrated significant improvements in compressive, tensile and flexural strength due to fiber addition. The study also shows how different fibers alter crack propagation and failure modes. Research by Wang (2025) reinforced that varying fiber type and content significantly affects concrete's mechanical properties, including a marked improvement in crack resistance and compressive strength when optimum fiber dosages are employed. Finally, Arvizu-Montes et al. (2025) investigated the mechanical performance of FRC with polypropylene and alternative fibers, showing that fiber inclusion enhances flexural strength and ductility without severely compromising workability, while ultrasonic pulse velocity (UPV) measurements confirmed internal integrity improvements.

Durability is a critical aspect of FRC research, as fiber inclusion can significantly affect concrete's resistance to environmental degradation, permeability, and long-term performance. A recent comprehensive review by M Anas (2022) showed that fibers improve tensile and flexural strengths while also reducing shrinkage cracks and enhancing durability performance. However, challenges such as reduced workability were noted. Another important contribution by Porfyriadou et al. (2025) investigated hybrid fiber approaches, combining polymeric and steel fibers, demonstrating how short discontinuous fibers improve dispersion, ease of mixing, and potentially mechanical performance under service conditions. The hydrophobic nature of polypropylene fibers was explored by Mohamed (2024), who found that incorporating these fibers can reduce water infiltration and improve durability metrics, although limitations due to weaker fiber-matrix bonds were also observed. In terms of specialized durability insights, Justin (2025) examined the effects of fiber-reinforced concrete under acidic exposure, showing that adding a mix of natural and engineered fibers with silica fume enhanced compressive and tensile strengths, suggesting increased resistance against chemically aggressive environments. Lastly, a critical evaluation by Abdulkareem (2022) reviewed how polypropylene fiber inclusion influences concrete durability, covering key indices such as water absorption, permeability, chloride diffusion, and freeze-thaw resistance, confirming that fibers can block harmful ion ingress and improve long-term performance under variable environmental conditions.

4.2. Steel Fiber

Recent research continues to demonstrate that steel fibers significantly enhance the mechanical performance of conventional and high-performance concrete. Zheng et al. (2024) presented a detailed review of 137 studies on steel fiber-reinforced concrete (SFRC), concluding that steel fibers increase toughness, fracture resistance, elastic modulus, and crack control, particularly when fiber length, aspect ratio, and dosage are optimized.

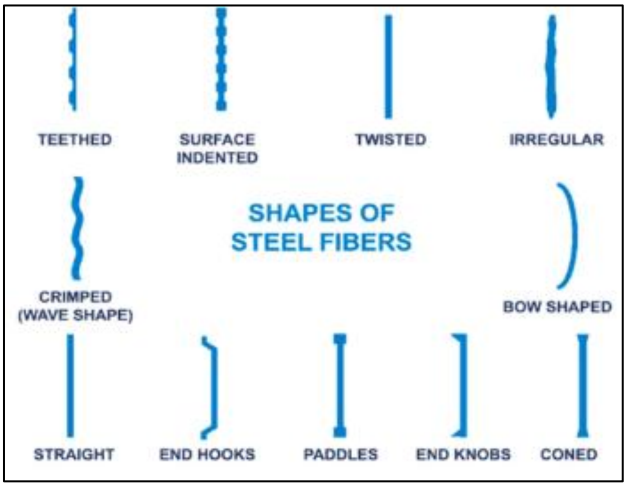

Figure 2 Types of Steel Fiber

Their review emphasizes how steel fibers improve the load-deflection response and post-peak ductility of concrete mixes across multiple applications. In a 2025 study, Wang et al. (2025) investigated the behavior of SFRC linings in tunnels, reporting that the addition of steel fibers increased compressive stress by approximately 22.2% compared to conventional concrete under load and significantly improved stiffness and deformation capacity. These results confirm the value of steel fibers in structural concrete applications subjected to complex loading conditions. Liao et al. (2025) explored the influence of steel fiber content (0–3% by volume) on ultra-high-performance concrete (UHPC). They found that increasing steel fiber content enhanced energy absorption, toughness, and impact resistance, especially under dynamic load, while maintaining acceptable workability highlighting an optimal 2% fiber content as the most balanced mix for performance and flowability. Focusing on sustainable mixtures, Ortiz-Lozano et al. (2025) evaluated steel fiber reinforced self-compacting concrete made with 100% recycled coarse aggregates, showing that steel fiber addition can maintain durability and compressive performance even in environmentally friendly mixes. Jin et al. (2024) conducted an experimental study on UHPC containing coarse aggregate at temperatures down to −90 °C, demonstrating that steel fiber content up to 3% markedly increased uniaxial compression and splitting tension strength, even in extreme cold.

Beyond mechanical performance, recent studies have explored how steel fibers influence the durability and long-term behavior of concrete. Shang & Wen (2025) investigated the impact of graphene oxide (GO) on the durability of steel fiber reinforced concrete (SFRC) under different corrosion environments. Their findings revealed that combined GO and steel fibers altered microstructure and improved resistance to salt and sulphate environments, suggesting enhanced long-term integrity under aggressive exposure. A focused corrosion study by Liu et al. (2024) examined SFRC under stray current and chloride attack, showing that increased steel fiber content decreased electrical resistance and accelerated corrosion of embedded reinforcement due to enhanced conductive paths, but thicker concrete cover countered this effect highlighting a complex interaction between fibers, corrosion and cover depth. In terms of structural application, ElHamahmy (2025) conducted a comprehensive review of steel fiber use in concrete slab repair and retrofit. The review reported that steel fibers can improve flexural strength by up to 51.7%, splitting tensile strength by 14–24%, substantially reduce crack widths, and extend service life by 25–50%, supporting enhanced durability in repair contexts. Wen et al. (2025) evaluated SFRC subjected to 150 freeze-thaw cycles, finding that appropriate nano-additives and steel fibers reduced mass loss by over 40% and increased elastic modulus by ~7.7%, indicating superior frost resistance compared to plain concrete. Lastly, Saravanan et al. (2025) investigated recycled aggregate concrete reinforced with steel fibers. They confirmed that steel fiber reinforcement compensates for the weaker aggregate matrix, improving impact resistance and ductility, which are crucial for durability in recycled concrete applications.

Table 2 Research on Steel Fiber Reinforced Concrete (SFRC)

Author & Year	**Method / Material**	**Results (Values)**	**Key Findings**
Wang et al. (2025)	Small-scale model & ABAQUS simulation of SFRC linings	+22.18% compressive stress and increased stiffness compared to conventional concrete	Steel fibers improve stress distribution and reduce reinforcement needs in tunnel structural linings
Wen et al. (2025)	Optimization of SFRC freeze-thaw durability (MDPI)	After 150 cycles: mass loss <5%; dynamic elastic modulus ↑ relative dynamic performance vs control	Steel fibers (plus nanoparticle additives) reduced freeze-thaw damage and preserved mechanical integrity
Alkhafaji (2025)	Mechanical property study of concrete with micro steel fibers	0.8% SF: +15% compressive, +39.2% split tensile, ~85% flexural strength	Small doses of steel fibers significantly increase mechanical performance
Premkumar (2025)	ANN model prediction of SFRC strength under elevated temperatures	ANN successfully predicted compressive, flexural, split tensile strength with high accuracy (R^2 > 0.94)	Predictive modeling supports design under thermal stress conditions
Liang et al. (2025)	Steel fiber alignment and content impact study	Varying volume fractions (1–3%) improved flexural strength 40–80%; dense matrix reduced porosity <6%	Higher SF content in UHPC improves durability metrics like chloride resistance

Table 2 presents research on Steel Fiber Reinforced Concrete (SFRC), highlighting key findings from various studies. Wang et al. (2025) demonstrated that steel fibers improve stress distribution and stiffness in tunnel linings, leading to a 22.18% increase in compressive stress. Similarly, Wen et al. (2025) found that steel fibers, combined with nanoparticles, reduced freeze-thaw damage, preserving mechanical integrity after 150 cycles. Alkhafaji (2025) reported a significant increase in compressive and split tensile strength with just 0.8% steel fiber, while Premkumar (2025) highlighted the accuracy of ANN models in predicting strength under elevated temperatures. Finally, Liang et al. (2025) concluded that steel fiber content improves flexural strength and reduces porosity, enhancing durability.

4.3. Polyester Fibers

In recent years, polyester fibers have received increasing attention as a synthetic reinforcement in concrete systems due to their crack-bridging ability, enhancement of tensile strength, and improvement in overall performance of cementitious materials. Mohsin Ali et al. (2025) conducted an extensive experimental study on high strength concrete (HSC) of grade C60 with varying contents of polyester fiber (0%, 0.2%, 0.3%, 0.4%, and 0.5%). The results demonstrated that the inclusion of polyester fiber significantly enhanced both compressive strength and split tensile strength. At an optimal 0.3% fiber content, compressive strength increased by 14.17% compared with the control mix, while split tensile strength showed improvements of 40.63% at 0.2% fiber and 65.68% at 0.3% fiber after 28 days of curing.

Figure 3 Polyester Fibers

Although the workability (slump) decreased with higher fiber content, ranging from a 14% to 57% slump reduction, no bleeding or segregation was observed—indicating that fiber distribution remained uniform and stable. Another recent contribution, R Ashwathi et al. (2025), investigated the hybrid incorporation of steel and polyester fibers in concrete. This study highlighted that while steel fibers significantly boost tensile strength and crack resistance, polyester fibers play a vital role in enhancing toughness and impact resistance under varied loading conditions. The hybrid fiber composite exhibited improved performance over conventional concrete in both tensile and flexural behavior, suggesting that polyester fibers help distribute stresses and prevent early micro-crack propagation when combined effectively with other fibers. In addition, studies focusing on polyester fibers in ultra-high performance and reactive powder concretes reported enhanced spalling resistance and durability under elevated temperature conditions when polyester fibers were used in conjunction with other synthetic fibers. For instance, P Hiremath et al. (2023) observed that a combined polypropylene and polyester fiber blend demonstrated superior spalling and residual mechanical properties in reactive powder concrete at temperatures up to 800 °C, with a 0.5% fiber content showing optimal resistance.

Beyond mechanical strength enhancements, polyester fibers have been explored for their effects on the durability and environmental performance of concrete. The incorporation of polyester fibers has been shown to control shrinkage cracking, limit micro-crack development, and improve long-term serviceability in structural elements. For example, in high strength concrete applications, the addition of polyester fibers at optimal contents not only increased the compressive and tensile strengths but also led to improved resistance against micro-structural degradation over curing periods extending to 28 days and beyond, making them suitable for structural elements where long-term durability is critical. In hybrid concrete systems, the synergy between polyester and other fibers has been leveraged for resilience under dynamic loads and environmental stresses. While steel fibers primarily enhance load-bearing capacity and crack closure, polyester fibers contribute by bridging micro-cracks and distributing stress more uniformly, reducing the potential propagation of cracks that lead to durability issues such as carbonation or chloride ingress. Studies like R Ashwathi et al. (2025) emphasized this synergistic effect, suggesting improved composite behavior under service conditions compared to mono-fiber mixes. Additionally, polyester fibers have practical advantages in industrial and precast applications due to their corrosion-free nature and compatibility with concrete admixtures. Unlike metallic fibers, polyester does not corrode in the alkaline environment of concrete, which can contribute to sustained performance in aggressive environments without deteriorating the reinforcement itself. This corrosion resistance is particularly valuable in structures exposed to climates with frequent wet-dry cycles, marine conditions, or deicing salts. Polyesters' lightweight nature also helps maintain concrete's workability when used at recommended dosages, ensuring that concrete can be placed effectively without significant reduction in flowability.

Table 3 Polyester Fiber and Hybrid Fiber Reinforced Concrete

Author (Year)	Material/Fiber Content	Methodology / Tests	Results / Values	Key Findings
Mohsin Ali, Aneel Kumar & Samar Hussain Rizvi (2025)	Polyester fiber 0–0.5% in HSC (C60)	90 concrete mixes; compressive & split tensile strength at 3–28 days	14.17% ↑ compressive strength at 0.3%; 40.63% ↑ split tensile at 0.2%; 65.68% ↑ split tensile at 0.3%	Optimal polyester fiber improves both strength parameters; slump ↓ with fiber content but no segregation observed.
Chella Gifta Christopher et al. (2023)	Hybrid (steel + polyester) fibers in M45 (~0.2–0.5%)	Mechanical & durability tests; electrical conductivity	Compressive strength ↑ ~14% at 0.5%; electrical conductivity ↑ from 12.764 → 17.688 mS/m with increased polyester content	Hybrid system improves compressive strength and durability indicators; polyester alone improves strength marginally but helps crack control.
Y Jia (2025)	Modified polyester fiber + basalt fiber hybrid	Mechanical & durability tests under aggressive conditions	Composite test values (compressive >50 MPa; tensile ~3 MPa)	Modified polyester and basalt hybrid improved mechanical performance & durability under sulfate cycles.
Vadivel et al. (2025)	HFRC with steel + glass + polypropylene	Compressive, tensile, flexural tests; SEM	Compressive ↑ 20–25%; tensile ↑ ~30%; flexural ↑ ~35%	Hybrid fibers significantly improve mechanical performance and microstructural bonding.
R Ashwathi (2025)	Steel + Polyester hybrid	Structural behavior tests	Hybrid improves crack resistance, tensile behavior	Synergistic effect of hybrid fibers enhances overall mechanical performance vs mono-fiber.
(Various Syntheses) RK Mishra (2025)	Synthetic fibers incl. polyester (0.5–1%)	Literature review on synthetic fibers in concrete	Compressive ↑ 21%; tensile ↑ 15%; flexural ↑ 16% (synthetic fibers incl. polyester)	Polyester reinforces compressive and tensile properties up to an optimum percentage.

Table 3 highlights the performance of Polyester Fiber and Hybrid Fiber Reinforced Concrete across various studies. Mohsin Ali et al. (2025) demonstrated that polyester fibers in HSC (C60) increased compressive strength by 14.17% and split tensile strength by up to 65.68% at optimal fiber content. Chella Gifta Christopher et al. (2023) found that hybrid fibers (steel + polyester) in M45 concrete improved compressive strength by 14% and electrical conductivity. Y Jia (2025) reported enhanced compressive and tensile strength with modified polyester and basalt fibers, particularly under sulfate conditions. Vadivel et al. (2025) showed significant improvements in compressive, tensile, and flexural strength in HFRC with hybrid fibers. Finally, RK Mishra (2025) concluded that polyester fibers enhanced both compressive and tensile strength in synthetic fiber mixes.

4.4. Hybrid Fiber Reinforced Concrete (HFRC)

Several recent studies have investigated the mechanical performance and microstructural behavior of Hybrid Fiber Reinforced Concrete (HFRC), highlighting the synergistic effects of combining different fiber types. One of the most recent and comprehensive experimental investigations was conducted by Vadivel et al. (2025), who studied HFRC mixtures incorporating steel, glass, and polypropylene fibers in varying proportions. The study reported that optimized HFRC mixes achieved 20–25% increases in compressive strength, ~30% enhancement in split tensile strength, and up to 35% improvement in flexural strength compared to plain concrete. The modulus of elasticity also increased by 15–20%, indicating stronger load transfer and stiffness due to fiber bridging effects. Workability remained acceptable, with slump loss not exceeding 15%, thanks to superplasticizer use. Scanning electron microscopy (SEM) confirmed improved fiber–matrix bonding and denser interfacial transition zones, which limit crack propagation and improve durability. In another significant contribution, Tong et al. (2025) examined the dynamic mechanical properties of HFRC under varying temperatures and strain rates using Split Hopkinson Pressure Bar (SHPB) techniques. Their study demonstrated that the steel fiber content dominated compressive and tensile strengths, whereas polypropylene fibers were crucial for enhancing HFRC's tensile performance. Under high-temperature conditions, HFRC maintained superior dynamic compressive strength and toughness compared to ordinary concrete, with peak performance shifts dependent on temperature and fiber volume fractions. Optimal mixes included ~0.5% steel fiber and ~0.1% polypropylene fiber, showing ~50% increase in tensile strength and ~10% increase in compressive strength relative to non-hybrid mixes under dynamic loads. A comprehensive review by Ma et al. (2024) systematically analyzed the *quantitative hybrid effects* in HFRC, comparing mechanical properties, durability, and fatigue performance across various fiber combinations. The review highlighted that hybridization improves crack control, energy absorption, and ductility, particularly when fibers of different scales and stiffness are synergistically combined. It concluded that while hybrid fibers enhance mechanical performance and durability, further research is needed to optimize fiber ratios and understand negative hybrid effects on workability and shrinkage. In addition, Akbulut (2025) assessed hybrid systems combining steel and synthetic fibers, showing that steel fibers significantly raise fracture toughness and tensile strength, while synthetic fibers help reduce micro-cracking and enhance long-term durability. SEM analyses confirmed better interfacial bonding and reduced micro-crack networks in hybrid mixes than mono-fiber systems.

While mechanical properties are critical, recent research has also focused on the durability and environmental performance of HFRC under various exposure conditions. A key study by Vadivel et al. (2025) showed that HFRC with optimized fiber combinations not only improved mechanical metrics but also exhibited enhanced microstructural integrity, which is closely linked to long-term durability by reducing pathways for moisture and chemical ingress. The denser matrix and stronger fiber–matrix interfacial zones delay micro- and macro-crack growth, which is crucial for resisting environmental deterioration. The dynamic performance work by Tong et al. (2025) further contributes to durability understanding by demonstrating that HFRC maintains higher dynamic compressive and tensile properties across a range of high temperatures. This suggests thermal resilience and structural stability, making HFRC a promising solution for infrastructure in extreme thermal or high strain rate environments where conventional concrete may fail. Recent reviews, such as that by Ma et al. (2024), have also emphasized durability metrics including fatigue resistance, crack propagation behavior, and constitutive modeling of HFRC across multiple studies. The review notes that hybrid fibers not only bridge cracks effectively but also distribute stresses across micro- and macro-scales, delaying damage accumulation under cyclic loads. Another relevant study by Akbulut (2025) examined how different hybrid fiber proportions affect workability and durability, reporting that while steel fibers enhance strength and stiffness, synthetic fibers improve ductility and shrinkage control, which indirectly reduces susceptibility to environmental damage such as freeze–thaw cycles and chloride penetration. SEM imagery showed fewer micro-voids and tighter fiber networks in hybrid mixes, contributing to improved durability performance. Emerging research also explores thermo-mechanical behavior, such as by M Ali (2025), which investigates HFRC's response to combined thermal and dynamic stresses, offering critical insights for fire-resistant structural design. These durability assessments underline that HFRC not only provides enhanced mechanical performance but also offers extended service life potential under multi-hazard conditions, advancing it as a superior material for modern construction applications.

Table 2 Hybrid Fiber Reinforced Concrete (HFRC)

Author (Year)	**Material / Method**	**Results**	**Key Findings**
Christopher et al. (2023)	Studied steel + polyester fibers in M45 concrete with fly ash & silica fume; performed compressive, tensile, and durability tests	Compressive ↑ up to 14% with 0.5% fibers; electrical conductivity ↑ from 12.764 to 17.688 mS/m; water absorption ↓ 10–20%	Hybrid addition improves mechanical strength, toughness, conductivity, and durability compared to plain concrete
Vadivel et al. (2025)	Experimental HFRC with steel, glass & polypropylene fibers; SEM & mechanical tests	Compressive, tensile, flexural tests show significant	Hybrid fibers enhanced mechanical performance and microstructural bonding

		performance gains; SEM confirmed crack bridging	
Porfyriadou (2025)	HyFRC with steel + PP fiber braid; microstructural & mechanical performance	Max compressive 56.7 MPa (~59% ↑), flexural load 20,159 N (~2× control); hybrid mixes >46 MPa	Synergistic effect improves strength, microstructure, and ductility
Akbulut (2025)	Review on crack resistance, mechanical properties, SEM analysis	-	Detailed mechanisms of crack bridging and fiber–matrix interaction
Wei (2025)	Experimental HFRC with multiple fiber blends (steel, PVA, PP, BF, GF) + FE modeling	Hybrid fibers outperformed single fibers in mechanical tests; FE model validated flexural toughness	Hybrid design choices strongly influence mechanical performance
Hu (2025)	Self-compacting hybrid steel fiber concrete; DIC strain measurement	Compressive strength ↑ 41.15% vs control; macro cracks retarded significantly	Steel fibers improve crack resistance and flexural–tensile behavior
Zhang et al. (2025)	Steel-PPF hybrid cement composite	PPF replacement increases slump up to 13%; split tensile ↑ 16.82% at 20% replacement	Hybrid % design can optimize workability & durability

Table 2 presents research on Hybrid Fiber Reinforced Concrete (HFRC), emphasizing material combinations and mechanical and durability improvements. Christopher et al. (2023) found that hybrid fibers of steel + polyester in M45 concrete improved compressive strength by 14% and electrical conductivity, while water absorption decreased by 10–20%. Vadivel et al. (2025) highlighted significant gains in compressive, tensile, and flexural strength with a steel-glass-polypropylene fiber blend, with SEM analysis confirming crack bridging. Porfyriadou (2025) showed 56.7 MPa compressive strength with steel + PP fibers, doubling the flexural load capacity. Akbulut (2025) reviewed crack resistance mechanisms in HFRC, detailing fiber-matrix interactions. Wei (2025) demonstrated that hybrid fiber blends (steel, PVA, PP, BF, GF) improved flexural toughness, validated by FE modeling. Hu (2025) reported 41.15% increase in compressive strength with self-compacting steel fiber concrete, significantly improving crack resistance. Finally, Zhang et al. (2025) found that hybrid designs with PPF improved workability and durability, with a 16.82% increase in split tensile strength at 20% replacement.

5. Discussion

The research on Hybrid Fiber Reinforced Concrete (HFRC) has consistently demonstrated that combining different types of fibers, such as steel, polyester, polypropylene, and glass, leads to significant improvements in the mechanical properties and durability of concrete. A study by Christopher et al. (2023) on steel and polyester fibers in M45 concrete with supplementary materials such as fly ash and silica fume reported up to a 14% increase in compressive strength with 0.5% fiber content. Additionally, the hybrid mix demonstrated improved electrical conductivity and a 10–20% reduction in water absorption, indicating that the combination of steel and polyester fibers not only enhanced the mechanical performance but also improved the durability by reducing the permeation of harmful agents. These findings are consistent with Vadivel et al. (2025), whose work on steel, glass, and polypropylene fibers showed significant improvements in compressive, tensile, and flexural strengths. The scanning electron microscopy (SEM) results confirmed that the hybrid fibers improved the microstructure of the concrete, especially in terms of crack bridging, which is crucial for increasing the longevity and resilience of concrete structures.

The synergistic effect of hybrid fibers has been particularly notable in studies like that of Porfyriadou (2025), where the combination of steel and polypropylene fibers led to a 56.7 MPa compressive strength, representing a 59% improvement compared to conventional concrete. Moreover, this combination also increased flexural load capacity significantly, with values reaching 20,159 N, which was almost double that of control samples. This clearly highlights how hybrid fiber systems can significantly enhance the strength and ductility of concrete, making it more suitable for applications subjected to high stress and dynamic loading. Additionally, research by Wei (2025) demonstrated that multiple fiber blends, including steel, PVA, PP, basalt, and glass fibers, not only performed better than single-fiber systems but also confirmed through finite element (FE) modeling that these designs contributed to improved toughness and flexural performance. The ability of hybrid fibers to optimize workability and durability is further supported by findings from Zhang et al. (2025), who reported that PPF replacement increased slump and split tensile strength, thereby improving the overall performance of the concrete. These studies underscore the importance of fiber type selection and fiber content optimization to achieve the desired mechanical strength and long-term durability in hybrid fiber concrete systems.

6. Conclusion

In conclusion, the review of hybrid steel–polyester fiber reinforced concrete (HyFRC) reveals its substantial advantages in enhancing both mechanical toughness and durability over conventional concrete. The synergy between steel and polyester fibers combines their distinct properties, resulting in a composite material that performs well in both strength and long-term durability. Steel fibers significantly contribute to improved compressive strength, crack resistance, and toughness, particularly under dynamic loading conditions, while polyester fibers offer benefits such as enhanced ductility, reduced shrinkage cracking, and superior resistance to environmental degradation. The hybridization not only enhances post-crack energy absorption but also addresses common issues such as fiber dispersion and workability challenges seen in mono-fiber systems. Additionally, polyester fibers' corrosion resistance in harsh environments further extends the service life of the material. Studies consistently demonstrate that the combination of these fibers in concrete improves structural resilience, reduces water absorption, and enhances durability under aggressive exposure conditions like chloride attack and freeze-thaw cycles. The findings emphasize the growing relevance of HyFRC as a high-performance composite material, suited for diverse applications including pavements, bridges, and industrial floors. As the demand for sustainable and durable infrastructure grows, HyFRC represents a promising solution, combining both mechanical enhancements and long-term durability benefits, thereby meeting the increasing industry requirements for resilient construction materials. Future research should focus on optimizing fiber combinations and exploring eco-friendly alternatives to further enhance the sustainability of HyFRC in modern construction.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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