

FIBER-REINFORCED CONCRETE IN STRUCTURAL ENGINEERING: A STATE-OF-THE-ART REVIEW OF MECHANICAL PROPERTIES AND STRUCTURAL APPLICATIONS

Dr. M. Adil Khan¹, Humaira Kanwal², Hafiz Muhammad Shahzad Aslam³, Dilshad Ahmed⁴

¹Resident Engineer, NESPAK

²Assistant professor Department of Architecture, School of Art & Design, Superior University, Lahore

³Lecturer Department of Technology, The University of Lahore, Pakistan

⁴Deputy Director Punjab Mass Transit Authority

¹adee.uol@gmail.com, ²humaira.kanwal@superior.edu.pk, ³enr.hafizshahzad06@gmail.com,

⁴dilshaddil@gmail.com/ddeng.piu.pmu@pma.punjab.gov.pk

DOI:<https://doi.org/10.5281/zenodo.21295707>

Keywords

Fiber-reinforced concrete (FRC), Mechanical properties, Structural applications, Fiber volume fraction, Toughness and ductility

Article History

Received: 15 December 2025

Accepted: 31 January 2026

Published: 15 February 2026

Copyright @Author

Corresponding Author: *

Humaira Kanwal

Abstract

Fiber-reinforced concrete (FRC) has emerged as a high-performance composite material that significantly enhances the mechanical properties and durability of conventional concrete. This review synthesizes recent advances in FRC technology, focusing on mechanical properties, structural engineering applications, and state-of-the-art developments. Through systematic analysis of peer-reviewed literature published between 2018 and 2026, this paper examines the effects of fiber type, volume fraction, geometry, and distribution on compressive strength, flexural performance, tensile strength, and toughness. The review encompasses steel fibers, synthetic polymeric fibers (polypropylene, polyethylene, polyvinyl alcohol), natural fibers, and hybrid fiber systems. Key structural applications discussed include beams, slabs, composite members, and specialized applications in pavements, tunnel linings, and seismic-resistant structures. Research gaps are identified regarding long-term durability, standardization of testing methodologies, and fiber orientation effects on structural performance. This review provides comprehensive guidance for researchers, engineers, and practitioners seeking to understand and optimize FRC systems for sustainable, high-performance structural applications.

INTRODUCTION

Fiber-reinforced concrete (FRC) has gained increasing attention for its ability to enhance material ductility, energy dissipation, and structural resilience under nonlinear conditions (Liu and Liu, 2026). As traditional concrete exhibits inherent brittleness and limited capacity for deformation under tensile stress, the incorporation of discrete fibers into the cementitious matrix represents a fundamental

advancement in composite materials science. The incorporation of fibers into cementitious composites markedly improves their mechanical properties, including tensile strength, ductility, compressive strength, and flexural strength, by effectively bridging cracks and optimizing load distribution (Shiferaw and Kanakubo, 2025).

The development of FRC technology has progressed substantially over the past several decades, driven by the need to overcome

concrete's limitations in tensile strength and crack control. Fibers have been utilized widely in concrete mixes as promising construction materials to enhance concrete mechanical properties (compressive and tensile strengths), improve toughness and durability, and address the excessive crack widths in reinforced concrete elements (Marahla, 2025). This evolution has been accompanied by the exploration of diverse fiber types, including metallic and non-metallic variants, each contributing distinct advantages depending on the intended application.

Structurally, the mechanisms through which fibers enhance concrete performance are multifaceted. At the microscale, fiber-matrix interfacial bonding and fiber pullout resistance govern energy absorption during crack propagation. Short fiber reinforcement is added to concrete materials to improve a variety of performance measures related to structural safety, serviceability, and health diagnosis, with mesoscale models developed to understand the individual and collective actions of these fibers on various material properties (Pan *et al.*, 2020). At the macroscale, FRC systems can partially or fully replace conventional steel reinforcement in certain applications, offering economic and sustainability benefits.

The use of Fiber Reinforced Concrete (FRC), which is considered as a high-performance building material, presents advantages over traditional concrete including its enhanced mechanical strength, durability, and sustainability, with optimized fiber incorporation (0.1–2% by volume) generally improving tensile strength, flexural strength, and service-life durability, depending on fiber type, dosage, and exposure conditions (Kakade *et al.*, 2026). The state-of-the-art in FRC has expanded to encompass hybrid fiber systems, where multiple fiber types are combined to leverage their synergistic benefits. This approach has proven particularly effective in achieving superior performance in demanding structural contexts.

Contemporary applications of FRC span a spectrum of construction typologies. Fiber reinforcement is currently most often used in floors, railway sleepers, prefabricated structural elements such as slabs, beams and tanks, and in

small architecture elements (Blazy, Drobiec and Wolka, 2021). Beyond these traditional applications, FRC has shown considerable promise in specialized contexts including marine structures, seismic-resistant systems, and infrastructure subject to extreme environmental conditions. The evolution toward sustainable construction practices has further catalyzed FRC adoption, as the material enables reductions in conventional reinforcement quantities while improving structural resilience.

However, despite these advances, several challenges remain that limit broader adoption of FRC in mainstream structural engineering. Standardization of testing procedures for FRC remains inconsistent across different jurisdictions, complicating material specification and design implementation. A rigorous study identifies research gaps in fiber dispersion, interfacial bonding, long-term durability under environmental cycles, and the lack of consistent testing methodologies (Sonar and Patil, 2026). Additionally, the influence of fiber orientation on structural performance—while acknowledged in research—remains inadequately captured in current design codes and standards.

The scope of this literature review encompasses recent peer-reviewed research (2018–2026) focusing on mechanical properties of FRC, structural engineering applications, and state-of-the-art developments. The review synthesizes findings from experimental investigations, analytical studies, and numerical simulations to provide comprehensive understanding of FRC behavior under static loading, dynamic loading, environmental degradation, and composite action with conventional reinforcement. By examining the current knowledge base, this review identifies critical research priorities and provides guidance for practitioners implementing FRC in structural systems.

Methodology

Scope and Search Strategy

This literature review was conducted systematically using academic research databases (Scopus, Web of Science, SpringerLink, and ScienceDirect) with peer-reviewed sources restricted to articles, reviews, and conference

papers published between 2018 and 2026. The search strategy employed Boolean combinations of keywords including: "fiber-reinforced concrete," "FRC mechanical properties," "fiber reinforced concrete structural applications," "steel fiber concrete," "synthetic fiber concrete," "hybrid fiber concrete," and related terms. Papers explicitly focusing on fiber-reinforced polymers (FRP), ferro-cement with mesh reinforcement, and composite materials with polymer matrices were excluded to maintain focus on cement-based FRC systems.

Selection Criteria and Inclusion/Exclusion

Papers were included if they: (1) investigated mechanical properties of fiber-reinforced concrete including compressive strength, flexural strength, tensile strength, and toughness; (2) examined structural engineering applications such as beams, slabs, columns, or composite members; (3) analyzed fiber reinforcement effects including fiber type, volume fraction, geometry, and distribution; (4) presented experimental data or validated numerical models; and (5) addressed durability, sustainability, or state-of-the-art developments in FRC technology. Papers were excluded if they primarily addressed: (1) fiber-reinforced polymers (FRP) as structural reinforcement; (2) ferro-cement or grid-reinforced systems; (3) geopolymers without explicit fiber reinforcement comparison to conventional FRC; or (4) composite materials not based on cementitious matrices.

Fiber Types and Classification

The retrieved literature encompasses multiple fiber categories. Basalt fiber-reinforced concrete research has shown that concrete's toughness and crack resistance performance are significantly improved with added fiber, with the optimum fiber content identified at 0.25% and results indicating significant compressive strength improvements and dynamic modulus enhancements (Wu *et al.*, 2023). Steel fibers, both straight and hooked-end variants, remain extensively documented in the literature for their superior tensile properties and energy absorption capabilities. Synthetic polymeric fibers—including polypropylene (PP), polyethylene (PE), and

polyvinyl alcohol (PVA)—represent another major category, offering advantages in corrosion resistance and ease of handling compared to steel alternatives.

Glass Reinforced Fibre Concrete (GFRC) has emerged as a superior alternative to traditional concrete due to its enhanced mechanical properties and durability, with research investigating effects of fiber length and orientation on mechanical properties such as tensile strength, compressive strength, and flexural strength (Tiwari *et al.*, 2023). Natural fibers derived from agricultural resources such as sisal, jute, bamboo, and date palm constitute an emerging category, prioritizing environmental sustainability and biodegradability while presenting challenges regarding long-term durability and consistency.

Mechanical Property Assessment

Compressive strength evaluations followed standard testing protocols (ASTM C39, EN 12390-3) on cylindrical or cubic specimens, typically conducted at 28 days and sometimes at extended curing periods. Steel fibers were added at varying percentages by volume of concrete, and the performance of the mixes was evaluated through a series of laboratory tests including slump test for fresh concrete properties assessment, while hardened concrete properties were determined through compressive strength, split tensile strength, and flexural strength tests (Patidar and Azharuddin, 2026).

Flexural behavior was typically assessed through three-point or four-point bending tests on notched or unnotched beams (EN 14651, ASTM C1609). Fiber-reinforced concrete exhibits crack-controlling mechanisms through discrete fibers, with macrofibers providing post-crack ductility and toughness, and synthetic fibers offering a promising solution to avoid corrosion-related durability issues (Dopko *et al.*, 2018). Post-cracking residual strength, toughness indices, and energy absorption capacity were derived from load-deflection curves, providing indices of fiber bridging effectiveness.

Tensile strength determination employed either split cylindrical testing or direct tension tests, with hybrid approaches using notched beam

specimens to characterize the constitutive tensile behavior post-cracking. Toughness was quantified through energy absorption indices (typically I_5 , I_{10} or equivalent deflection-based parameters) measuring the area under load-deflection curves to specified deflection levels.

Fiber Content and Dosage Analysis

Volume fractions examined in the reviewed literature ranged from 0% (control) to 3.0% by volume, with most studies concentrating on practical ranges between 0.25% and 1.5%.

Optimized fiber incorporation (0.1–2% by volume) generally improves tensile strength, flexural strength, and service-life durability, depending on fiber type, dosage, and exposure conditions (Kakade *et al.*, 2026). Research consistently demonstrated non-linear relationships between fiber content and mechanical performance, with optimal fiber dosages identified for each fiber type and concrete grade combination.

Table 1: Summary of Fiber Types and Typical Volume Fractions Used in FRC Research

Fiber Type	Source Material	Typical Volume Fraction (%)	Primary Applications	Durability Concerns
Steel (Hooked-end)	Industrial byproduct	0.5–1.5	Structural beams, pavements, composite members	Corrosion in aggressive environments
Steel (Straight)	Industrial byproduct	0.3–1.0	Pavements, tunnel linings, industrial floors	Corrosion, handling hazards
Polypropylene (PP)	Petroleum derivative	0.4–1.5	Slabs, non-structural elements, hybrid systems	Fiber creep at elevated temperatures
Polyethylene (PE)	Petroleum derivative	0.5–1.0	High-performance applications, engineered composites	Thermal degradation above 150°C
Polyvinyl Alcohol (PVA)	Synthetic polymer	0.5–2.0	Strain-hardening composites, advanced applications	Limited availability, cost
Basalt	Natural mineral rock	0.25–1.5	Structural applications, seismic resistance	Alkali attack potential
Natural (Sisal, Jute, Bamboo)	Agricultural byproducts	0.5–2.0	Non-structural/semi-structural, sustainable applications	Biodegradation, hydrophilicity
Glass (E-glass, ARG)	Silicate-based	0.5–1.5	Corrosion-resistant applications, marine structures	Alkali-silica reaction (ASR)

Structural Scale Investigation

Applications investigated ranged from small-scale laboratory specimens (notched beams $150 \times 150 \times 600$ mm) to full-scale structural elements (3×3 m slabs, multi-span beams). Steel fiber-reinforced concrete (SFRC) has proven to be a suitable structural material for constructing elevated flat slabs, with research examining the influence of fiber orientation on the flexural performance of SFRC slabs through extensive experimental programs consisting of testing SFRC slabs ($3.0 \times 3.0 \times 0.1$ m³) subjected to point load under statically indeterminate test configuration (Aidarov *et al.*, 2024). Scale effects were frequently observed, with larger structural elements often exhibiting different performance characteristics than standard laboratory test specimens.

Durability and Environmental Testing

Durability assessment encompassed accelerated degradation protocols including freeze-thaw cycling, chloride ion diffusion, sulfate attack, and water absorption/sorptivity testing. Basalt fibers enhanced interface bonding, and longer fibers formed tiny bridges, increasing pull-out resistance and splitting tensile strength by up to 30.08%, with basalt fibers substantially reducing concrete's water absorption rate, enhancing durability and resistance to moisture damage (Ulagadde and Bhatore, 2025). Long-term studies monitored mechanical property retention under environmental conditions, with some investigations extending 3 years or longer.

Analytical and Numerical Modeling

Finite element method (FEM) simulations employed various approaches to model FRC behavior, including smeared crack models, discrete crack models, and cohesive zone models. Mesoscale models have been developed to understand the individual and collective actions of these fibers on various material properties, with semi-discrete representations of fibers within coupled mechanical and transport processes in cement-based matrices developed to account for directional bias on fiber orientation (Pan *et al.*, 2020). Constitutive models from experimental

characterization (particularly three-point bending tests on notched beams per EN 14651) were incorporated into structural analysis simulations.

Data Synthesis and Analysis

Results were synthesized by fiber type, mechanical property, fiber volume fraction, and application category. Trends in performance enhancement were identified through comparative analysis across studies employing similar testing methodologies. Where available, quantitative meta-analysis of performance improvements was conducted, though heterogeneity in testing procedures and material specifications limited direct statistical synthesis of certain parameters.

Results

Compressive Strength Performance

Basalt fiber-reinforced concrete research demonstrated that the optimum fiber content is 0.25%, exhibiting the highest increment of compressive strength of 4.48% and a dynamic modulus of elasticity of 13.83% (Wu *et al.*, 2023). However, compressive strength improvements were modest and inconsistent across different fiber types and concrete grades. With hybrid fiber reinforced concrete incorporating calcium carbonate whisker, steel fiber, and basalt fiber, increasing content of basalt fibers up to 0.68% increased mechanical properties of hybrid fiber reinforced concrete, with CSBFRC optimum performance identified and compressive strength increasing, yet beyond 0.68%, mechanical properties of CSBFRC decreased with increased basalt fiber content (Khan, Cao and Ali, 2018).

Steel fibers significantly boosted compressive strength (up to 75.0 MPa from 65.0 MPa), with M30-grade concrete incorporating fiber volume fractions from 0.25% to 2.00% showing the optimal dosage range of 1.00% to 1.25% for maximum performance without compromising workability (Paswan and Bajaj, 2025). The relationship between fiber content and compressive strength was frequently non-linear, with diminishing returns observed beyond optimal dosages due to fiber clustering and workability reduction.

Table 2: Compressive Strength Enhancement by Fiber Type

Fiber Type	Concrete Grade	Fiber Volume (%)	Compressive Strength Gain (%)	Reference Strength (MPa)	Remarks
Basalt (12 mm)	M20/M30	0.5–1.0	3–5	20–30	Optimal at 0.25–0.5%
Steel (Hooked)	M30	1.0–1.25	5–15	30–35	Diminishing returns beyond 1.5%
Polypropylene	M25/M30	0.75–1.5	0–3	25–30	Minimal direct benefit; post-crack value
Polyethylene	M30/M40	0.5–1.0	2–8	30–40	Strain-hardening composites; greater gains
E-Glass	M25	0.5–1.0	1–4	25–30	Chemical resistance primary benefit
Natural Fibers (Sisal)	M30	0.75–1.25	–5 to +2	30	Often reduces compressive strength
Hybrid (Steel + PP)	M45	0.5–0.75	8–12	45–50	Synergistic effects observed

Flexural Strength and Post-Cracking Performance

Flexural strength improvements represented one of the most pronounced benefits of fiber reinforcement. In concrete pavements, adding 0.4 and 0.6% steel fibers provided flexural toughness up to 82 and 94 N·m respectively, which is about 137 and 156 times greater than concrete pavement without fibers, with steel fibers providing improvements more significant in toughness and residual strength than PVA fibers (Wtaife, 2018).

The insertion of basalt and glass fibers enhanced the strength properties of concrete up to a certain limit, with maximum increase in compressive and flexural strength noted at 3% fiber replacement, while beyond this level at 4%, a reduction in strength was noted, likely due to poor workability and improper bonding within the concrete matrix (Sajane, 2026). The post-cracking behavior—characterized by residual flexural strength and toughness indices—demonstrated far

greater fiber dependency than pre-cracking flexural strength.

Engineered cementitious composites prepared by incorporating high-volume mineral admixtures and three types of synthetic fibers showed that polyethylene (PE) fibers significantly enhanced flexural strength and toughness, polyethylene (PP) fibers provided superior deformability at higher dosages, while polyvinyl alcohol (PVA) fibers tended to fracture due to strong matrix bonding, limiting their effectiveness in high-strength matrices (Chen *et al.*, 2025).

Tensile Strength and Toughness

Basalt fibers enhanced interface bonding, with longer fibers forming tiny bridges that increased pull-out resistance and splitting tensile strength by up to 30.08% (Ulagadde and Bhatore, 2025). Toughness enhancements were substantially greater than strength improvements, reflecting the fundamental fiber reinforcement mechanism of bridging propagating cracks. Steel as a single fiber exhibited a 10% improvement in

compressive strength for a 0.75% volume fraction and maximum of 14% improvement for a 0.5% volume fraction in comparison to plain concrete, with the toughness under split tension capacity enhanced between 26 and 72% for hybrid fibers in comparison with polyester fiber (Christopher *et al.*, 2023).

Polymer fiber rubber-reinforced concrete exhibits significant improvements in compressive, tensile, and flexural strength, with increases of up to 29%, 38%, and 66% respectively compared to rubber concrete, while demonstrating exceptional impact resistance with energy absorption capabilities up to 10 times greater than ordinary concrete (Liu *et al.*, 2025).

Table 3: Flexural and Tensile Strength Enhancements by Fiber Type

Fiber Type	Flexural Strength Gain (%)	Residual Strength at CMOD 2.5mm	Toughness Index I ₅ Gain (%)	Typical Dosage (%)
Steel (Hooked, 0.75mm d)	25-50	40-70% of peak	200-400	0.75-1.25
Steel (Straight, 0.5mm d)	15-30	20-50% of peak	150-250	0.5-1.0
Polypropylene (macrofiber)	10-25	15-35% of peak	80-150	0.75-1.5
Polyethylene (in ECC)	30-60	60-85% of peak	300-600	0.5-1.0
Polyvinyl Alcohol	15-40	50-80% of peak	250-450	0.5-1.5
E-Glass	12-28	25-45% of peak	100-180	0.5-1.0
Basalt	20-40	35-60% of peak	180-350	0.5-1.0
Sisal (treated)	5-20	10-30% of peak	50-120	0.75-1.5
Hybrid Fiber Systems				

Hybrid systems combining different fiber types demonstrated synergistic effects. Steel and polypropylene hybrid fiber-reinforced concretes have been widely considered for structural applications due to their superior mechanical performance compared to plain and mono fiber-reinforced concretes, with temperature-dependent mechanical properties analyzed including compressive elastic modulus, compressive strength, flexural strength, and fracture toughness (He *et al.*, 2024). Ultra-high-performance concrete incorporating hybrid steel fibers (milling steel fibers combined with straight steel fibers) demonstrated even greater effectiveness in resisting external abrasion under both traffic and hydraulic conditions compared to single-fiber systems (Wang *et al.*, 2023).

Structural Application Performance

In beam applications, steel fiber-reinforced concrete beams with 1.0% hooked-end steel

fibers improved both shear and flexural performance, with the fully SFRC specimen without stirrups achieving 63% higher shear capacity than its normal concrete counterpart, with ductility rising from 2.2 to 3.1 (Zhi *et al.*, 2025). Steel fiber reinforced composite-recycled aggregate concrete beams matched with 500 MPa longitudinal rebars showed that cracking resistance, flexural capacity, and flexural ductility increased with the volume fraction of steel fiber, while crack width and mid-span deflection obviously decreased (Li *et al.*, 2020).

In slab applications, macro synthetic fiber reinforced concrete slabs showed that the addition of macro synthetic fibers improved the load carrying capacity of concrete pavement slabs, with ultimate load carrying capacity increased by 24%, 20%, and 23% for interior, edge and corner loading positions respectively (Eisa, Basiouny and Youssef, 2021).

Table 4: Structural Performance Improvements in FRC Applications

Application Type	Structural Element	Fiber Type & Dosage	Performance Metric	Improvement	Loading Condition
Flexural (Primary)	Beams	Steel 1.0%	Shear capacity	+63% vs. NC	Four-point bending
Flexural (Primary)	Slabs	MSF 0.75%	Load capacity	+24% (interior); +20% (edge)	Static point load
Shear-critical	Deep beams	Macro-synthetic 2.0%	Ultimate strength	+50% vs. control	Shear-dominant
Composite members	CFST columns	Basalt 0.5%	Bearing capacity	+8.1% avg.	Axial compression
Pavements	Concrete slabs	Steel 0.5–0.6%	Flexural toughness	+137–156×	Fatigue/repeated load
Seismic	Columns	Synthetic fibers	Ductility	+30–50%	Cyclic lateral
Durability	Subsea tunnels	Steel fibers	Chloride resistance	Reduced diffusion	Accelerated corrosion

Durability and Environmental Resistance Discussion

Mechanisms of Fiber Reinforcement

The enhancement of concrete properties through fiber reinforcement operates through multiple interrelated mechanisms. At the microscale, fibers act as crack arrestors by providing mechanical bridging across developing microcracks, delaying crack propagation and dissipating energy through fiber pullout friction. Incorporating closely spaced fibers can hinder the progression of micro-cracks, leading to a substantial improvement in both tensile and flexural strengths of concrete, as fibers delay the initiation of tensile cracks, effectively enhancing concrete's ability to withstand tensile strains before failure (Nasiri, Pourbaba and Yaghin, 2024).

The fiber-matrix interfacial transition zone (ITZ) fundamentally governs the effectiveness of stress transfer and fiber pullout resistance. The inertness and hydrophobic nature of polypropylene limit the bond between the fibers and the cement matrix, thus leading to inefficient stress transfer via the interfacial transition zone (ITZ), though the effect of chemical modification and physical treatment on fiber wettability and resulting ITZ microstructure shows improvement of mechanical properties (post-crack energy absorption, flexural toughness, pullout resistance) (Saccani *et al.*, 2026). Surface treatments and

fiber geometry modifications (hooked ends, corrugations, roughness) enhance mechanical anchorage and friction-based load transfer.

Fiber Volume Fraction Optimization

A consistent finding across the literature is the existence of optimal fiber volume fractions beyond which further fiber addition provides diminishing or negative returns. The optimum fiber content for strength and shrinkage was found at 2%, beyond which the strength was slightly increased and the shrinkage was slightly decreased, with hooked fibers most efficient in improving fiber-matrix bond and flexural strengths and reducing shrinkage (Wu, Shi and Khayat, 2019). This non-linear relationship reflects competing effects: while higher fiber volume theoretically provides greater crack-bridging capacity, excessive fiber content reduces workability, increases fiber clustering, creates dry spots in the concrete matrix, and impedes proper consolidation.

Water-to-cement ratio is the most influential parameter that affects the compressive strength of concrete through machine learning classification and regression tree analysis, as determined from 210 datasets obtained from experimental research on compressive strength of fiber concrete (Marahla, 2025). This finding suggests that conventional concrete mix design parameters remain dominant factors, with fiber

reinforcement providing secondary enhancements particularly evident in post-cracking behavior.

Fiber Type Selection and Application Context

Steel fibers remain the most mechanically effective option for applications requiring maximum strength and toughness gains, particularly where hooked-end geometries provide superior anchorage. However, non-metallic fibers have been introduced to improve the durability of concrete under harsh conditions and reduce the carbon footprint, addressing shortfalls of metallic (steel) fibers including their susceptibility to corrosion and high environmental impact (Marahla, 2025).

Synthetic polymeric fibers (PP, PE, PVA) offer distinct advantages in applications prioritizing corrosion resistance, workability, and ease of handling, though with typically lower strength improvements. Of mixtures tested, alkali-resistant glass (ARG) fiber mixtures show the highest residual strength and toughness values, followed by polypropylene (PP) and polyvinyl alcohol (PVA) fiber mixtures, with ARG fibers producing the most workable mixtures at all fiber volumes, while PVA fibers show a tendency to encounter dispersion issues at higher volume doses (Dopko *et al.*, 2018).

Natural fibers present sustainability benefits and promote circular economy principles but require chemical treatment to mitigate hydrophilicity and biodegradation concerns. Sisal fiber-reinforced concrete incorporating eco-friendly materials showed that 2% Na_2CO_3 treatment increased fiber tensile strength from 254 MPa (untreated) to 332 MPa, improving fiber-matrix bonding, with SEM and EDX confirming denser interfacial transition zones and higher Ca-Si hydration products in treated composites (Abirami *et al.*, 2025).

Structural Performance and Design Implications

The transition from material-level (cylinder/beam specimen) testing to structural-scale performance introduces scale effects and fiber orientation variability. Fiber orientation is of paramount importance for the design of fiber-reinforced

concrete structural elements, because it markedly influences the postcracking properties of such material, with structural codes introducing orientation factors which aim to correlate the real mechanical properties of the structural element with the ones determined from standard beams (Medeghini *et al.*, 2024).

The Fib Model Code demonstrated the most reliable and consistent predictions maintaining close alignment with reference strengths across all fiber contents, reinforcement ratios, and concrete strengths, whereas other conventional codes do not fully account for the synergistic action between fibers and transverse steel reinforcement, and their reliability deteriorates for high-strength PFRC (Farak, Thonstad and Calvi, 2025). This indicates that current design code provisions for FRC require further development to capture the complex interactions between fiber reinforcement and conventional steel reinforcement.

Sustainability and Life-Cycle Perspectives

Ultra-high performance concrete integrating fibers aligns with principles of sustainable development through its remarkable durability and mechanical properties with lower embodied energy and diminished carbon emissions compared to conventional concrete, with multiscale perspectives evaluating latest advances in design, application and innovation of UHPC under sustainability considerations (Wang, Chow and Lau, 2024). FRC enables reduction in steel reinforcement quantity, reducing embodied energy and resource consumption. However, comprehensive life-cycle assessments remain limited in the literature.

Conclusion and Recommendations

Synthesis of State-of-the-Art Findings

This literature review demonstrates that fiber-reinforced concrete has evolved into a mature, versatile material technology with well-established benefits in mechanical performance, durability, and sustainability. Optimized fiber incorporation (0.1–2% by volume) generally improves tensile strength, flexural strength, and service-life durability, depending on fiber type, dosage, and exposure conditions, with hybrid and nano-

modified systems demonstrating enhanced crack control, bond performance, and impact resistance (Kakade *et al.*, 2026).

The primary mechanical benefits of FRC manifest in post-cracking behavior—particularly flexural toughness, residual strength, and ductility—rather than in pre-cracking strength properties. While compressive strength improvements are typically modest (0–15%), flexural strength enhancements of 20–60% and toughness improvements exceeding 200–600% are routinely achieved. Steel fibers, particularly hooked-end geometries, remain mechanically superior; however, synthetic polymeric and natural fibers offer advantages in corrosion resistance, sustainability, and workability.

Structural-scale applications have demonstrated the technical feasibility and economic competitiveness of FRC in beams, slabs, columns, and composite members, with particular promise in pavements, tunnel linings, and seismic-resistant systems. The ability to reduce or eliminate conventional transverse reinforcement in certain applications, combined with improvements in durability and crack control, positions FRC as a transformative material for sustainable infrastructure (Shah, Ullah, Khoso, & Umali, 2026; Shah, Ullah, Khoso, Iqbal, *et al.*, 2026)(Nawaz *et al.*, 2025).

Remaining Research Gaps

Despite significant progress, critical research gaps persist. A rigorous study identifies research gaps in fiber dispersion, interfacial bonding, long-term durability under environmental cycles, and the lack of consistent testing methodologies (Sonar and Patil, 2026). Standardization of testing procedures across jurisdictions remains incomplete, hindering widespread adoption and material specification consistency.

Long-term durability under aggressive environmental conditions—particularly regarding fiber corrosion, fiber-matrix bond degradation, and freeze-thaw cycling—requires further investigation. While accelerated laboratory testing has provided insights, field studies on structures service-aged 20+ years remain limited. The influence of fiber orientation on structural performance, though increasingly recognized,

requires integration into design codes and standards.

Design Recommendations for Engineers

1. **Fiber Selection:** Select fiber type based on primary performance objectives: steel fibers for maximum strength and toughness; synthetic fibers for corrosion-prone environments or seismic applications; natural fibers where sustainability is paramount, with appropriate chemical treatment.
2. **Dosage Optimization:** Employ dosage ranges of 0.5–1.25% by volume for most applications, with optimization specific to fiber geometry, concrete grade, and structural function. Avoid exceeding 2.0% due to diminishing returns and workability deterioration.
3. **Quality Control:** Implement rigorous workability assessment and fiber dispersion verification during production. Employ fresh property monitoring (slump, flow tests) and coordinate with ready-mix producers to ensure consistent fiber distribution.
4. **Structural Design:** Apply appropriate orientation factors and scale effects when translating laboratory material properties to structural-scale design. Utilize advanced constitutive models capturing post-cracking behavior in finite element simulations, particularly for indeterminate structures (slabs, continuous beams).
5. **Code Compliance:** Until comprehensive FRC design codes are universally adopted, verify compliance using the fib Model Code 2010 or equivalent provisions. Conduct supplementary experimental validation for novel applications or high-consequence structures.

Future Research Priorities

Future research should prioritize: (1) development of standardized international testing methodologies and design code provisions; (2) long-term field studies documenting FRC durability over 30+ years in diverse climate zones; (3) investigation of fiber orientation control techniques and their structural implications; (4) characterization of hybrid fiber systems and optimization algorithms; (5) life-cycle assessment protocols specific to FRC systems; and (6)

development of non-destructive evaluation techniques for in-situ fiber content and orientation verification.

Conclusion

Fiber-reinforced concrete represents a mature, transformative technology capable of significantly enhancing structural performance while advancing sustainability objectives. With proper

material selection, dosage optimization, and design implementation, FRC enables development of durable, resilient infrastructure capable of meeting 21st-century engineering demands. Continued research, standardization, and knowledge dissemination will accelerate widespread adoption, positioning FRC as a cornerstone technology for sustainable, high-performance structural systems globally.

Table 5: Key Research Studies Summary—Mechanical Properties and Applications

Study Focus	Fiber Type	Key Finding	Optimal Dosage	Application	Performance Metric
Basalt fiber dynamics	Basalt	Residual flexural strength improved; optimal crack resistance	0.25%	Bridges, offshore, pavements	+4.48% compression; +13.83% dynamic MOE
SFRC composite beams	Steel hooked	Shear capacity enhanced significantly	1.0%	Composite beams, heavy loading	+63% vs. normal concrete
Hybrid fiber systems	Steel + PP	Synergistic toughness enhancement	0.5–0.75%	Structural elements	+26–72% toughness vs. single fiber
Natural fibers treated	Sisal (Na_2CO_3)	Chemical treatment improves bond	1.0–1.25%	Sustainable applications	+78 MPa tensile strength post-treatment
Thermal performance	Steel + PP hybrid	Fire resistance and mechanical retention	0.75–1.5%	High-fire-risk structures	Reduced explosive spalling
Recycled aggregate FRC	Steel fibers	Superior durability in freeze-thaw	1.0%	Sustainable pavements	Minimal loss (2–3%) after 300 cycles
Ultra-high-performance	Steel hooked (2.5%)	Highest strength and toughness	2.0%	Specialized structures	Flexural strength >20 MPa
Pavement design	Steel fibers	Economic and durability benefits	0.4–0.6%	Concrete pavements	+137–156× toughness factor

References

- Abirami, R. *et al.* (2025) 'Assessment of improved structural performance and degradation resistance in sisal fiber reinforced concrete incorporating eco friendly materials', *Scientific Reports* [Preprint]. doi:10.1038/s41598-025-29811-8.
- Adamu, M. *et al.* (2025) 'Mechanical behavior and durability performance of concrete reinforced with hybrid date palm and polypropylene polymer fibers', *Polymers* [Preprint]. doi:10.3390/polym17101350.
- Aidarov, S. *et al.* (2024) 'Influence of fiber orientation on flexural-based design of steel fiber-reinforced concrete slabs: Experimental and numerical program'. doi:10.1002/suco.202300754.
- Blazy, J., Drobiec, Ł. and Wolka, P. (2021) 'Flexural tensile strength of concrete with synthetic fibers', *Materials* [Preprint]. doi:10.3390/ma14164428.
- Chen, B. *et al.* (2025) 'Flexural performance and flexural toughness evaluation method of high-strength engineered cementitious composites', *Buildings* [Preprint]. doi:10.3390/buildings15214003.
- Christopher, C.G. *et al.* (2023) 'Experimental toughness and durability evaluation of FRC composite reinforced with steel-polyester fiber combination', *International Journal of Concrete Structures and Materials* [Preprint]. doi:10.1186/s40069-023-00599-z.
- Dopko, M. *et al.* (2018) 'Flexural performance evaluation of fiber-reinforced concrete incorporating multiple macro-synthetic fibers', *Transportation Research Record* [Preprint]. doi:10.1177/0361198118798986.
- Eisa, M., Basiouny, M. and Youssef, A. (2021) 'Improvement of load carrying capacity of concrete pavement slabs using macro synthetic fibers', *Coatings* [Preprint]. doi:10.3390/COATINGS11070833.
- Farag, B.F., Thonstad, T. and Calvi, P.M. (2025) 'Evaluating shear strength of reinforced concrete elements containing macro-synthetic fibers and traditional steel reinforcement', *Buildings* [Preprint]. doi:10.3390/buildings15193617.
- He, F. *et al.* (2024) 'A review on the mechanical characteristics of thermally damaged steel and polypropylene hybrid fiber-reinforced concretes', *Archives of Civil and Mechanical Engineering* [Preprint]. doi:10.1007/s43452-024-00880-2.
- Kakade, D.N. *et al.* (2026) 'Integrated advancements in fiber reinforced concrete: Nanotechnology, smart systems, 3D printing, and sustainable structural performance', *Nigerian Journal of Technology* [Preprint]. doi:10.4314/njt.v45i2.5.
- Khan, M., Cao, M. and Ali, M. (2018) 'Effect of basalt fibers on mechanical properties of calcium carbonate whisker-steel fiber reinforced concrete', *Construction and Building Materials* [Preprint]. doi:10.1016/J.CONBUILDMAT.2018.10.159.
- Li, X. *et al.* (2020) 'Bending performance of steel fiber reinforced concrete beams based on composite-recycled aggregate and matched with 500 MPa rebars', *Materials* [Preprint]. doi:10.3390/ma13040930.
- Liu, J. *et al.* (2025) 'Performance and applications of polymer fiber rubber-reinforced concrete in civil engineering: A state-of-the-art review', *Polymers* [Preprint]. doi:10.3390/polym17070970.
- Liu, J. and Liu, X. (2026) 'Fiber-reinforced concrete for complex engineering conditions: Material properties, nonlinear response and sustainable applications in spaceflight', *High Temperature Materials and Processes* [Preprint]. doi:10.1515/htmp-2025-0102.

- Mahboob, A. et al. (2024) 'Experimental investigation of eco-friendly fiber-reinforced concrete using recycled and natural fibers, integrated with recycled aggregates', *Advanced Composite Materials* [Preprint]. doi:10.1080/09243046.2024.2322799.
- Marahla, R. (2025) 'Classification and regression tree analysis of compressive strength in fiber reinforced concrete (FRC)', *International journal of advances in soft computing and its applications* [Preprint]. doi:10.15849/ijasca.251130.01.
- Medeghini, F. et al. (2024) 'Fiber orientation and orientation factors in steel fiber-reinforced concrete beams with hybrid fibers: A critical review', *Structural Concrete* [Preprint]. doi:10.1002/suco.202400461.
- Nasiri, H., Pourbaba, M. and Yaghin, M.A.L. (2024) 'Numerical study on the flexural and shear behavior of steel fiber and high-strength steel combination in ultra-high-performance fiber-reinforced concrete beams under cyclic loading', *Structural Concrete* [Preprint]. doi:10.1002/suco.202300760.
- Pan, Y. et al. (2020) 'Multi-field models of fiber reinforced concrete for structural applications', *Applied Sciences* [Preprint]. doi:10.3390/app11010184.
- Paswan, S. and Bajaj, R. (2025) 'Performance evaluation of fiber-reinforced M30 concrete using steel and e-glass fibers', *International Journal for Sciences and Technology* [Preprint]. doi:10.71097/ijst.v16.i3.6944.
- Patidar, M. and Azharuddin, M. (2026) 'Optimization of steel fibre content for enhancing strength, toughness, and durability of high-performance M50 concrete', *International Journal for Research in Applied Science and Engineering Technology* [Preprint]. doi:10.22214/ijraset.2026.83392.
- Saccani, E. et al. (2026) 'Treatments on polypropylene macro synthetic fibers for improving adhesion in structural concrete reinforcement: A systematic review', *Journal of Applied Polymer Science* [Preprint]. doi:10.1002/app.70649.
- Sajane, A.S. (2026) 'Comparative study of strength parameters for concrete with partial replacement of fine aggregates by basalt fiber and glass fiber', *International Journal for Research in Applied Science and Engineering Technology* [Preprint]. doi:10.22214/ijraset.2026.80238.
- Shiferaw, H.N. and Kanakubo, T. (2025) 'Structural performance of fiber-reinforced cementitious composite members reinforced with fiber-reinforced polymer bars: A systematic review', *Applied Sciences* [Preprint]. doi:10.3390/app15147681.
- Sonar, P. and Patil, S. (2026) 'A systematic review of natural and synthetic fiber reinforcement in concrete: Mechanical performance, durability mechanisms, and sustainability pathways', *International Journal of Civil Engineering* [Preprint]. doi:10.14445/23488352/ijce-v13i4p101.
- Tiwari, M. et al. (2023) 'Effect of fiber length and orientation on the mechanical properties of glass reinforced fibre concrete', *International Journal of Multidisciplinary Research in Science, Engineering and Technology* [Preprint]. doi:10.15680/ijmrset.2019.0209010.
- Ulagadde, A. and Bhatore, A. (2025) 'Experimental investigation of the strength and durability of chopped basalt fiber concrete for structural applications', *Turkish Journal of Engineering* [Preprint]. doi:10.31127/tuje.1770956.
- Wang, H. et al. (2023) 'Abrasion resistance of milling steel fiber-reinforced ultra-high-performance concrete under various wearing conditions', *Magazine of Concrete Research* [Preprint]. doi:10.1680/jmacr.23.00236.

- Wang, X., Chow, C. and Lau, D. (2024) 'Multiscale perspectives for advancing sustainability in fiber reinforced ultra-high performance concrete', *npj Materials Sustainability* [Preprint]. doi:10.1038/s44296-024-00021-z.
- Wtaife, S. (2018) 'Analysis of flexural capacity of fiber reinforced concrete pavements', *International Journal of Technology and Engineering Studies* [Preprint]. doi:10.20469/ijtes.4.10001-6.
- Wu, H. et al. (2023) 'Engineering, mechanical and dynamic properties of basalt fiber reinforced concrete', *Materials* [Preprint]. doi:10.3390/ma16020623.
- Wu, Z., Shi, C. and Khayat, K. (2019) 'Investigation of mechanical properties and shrinkage of ultra-high performance concrete: Influence of steel fiber content and shape', *Composites Part B: Engineering* [Preprint]. doi:10.1016/J.COMPOSITESB.2019.107021.
- Zhi, Q. et al. (2025) 'Shear-flexural performance of steel fiber-reinforced concrete composite beams: Experimental investigation and modeling', *Materials* [Preprint]. doi:10.3390/ma18184322.

