

FIBER-REINFORCED CONCRETE DEVELOPMENTS: A COMPREHENSIVE LITERATURE REVIEW OF MECHANICAL PROPERTIES, CRACK RESISTANCE, DURABILITY ENHANCEMENT, AND STRUCTURAL APPLICATIONS

Dr. M. Adil Khan^{*1}, Waqas Aziz², Dilshad Ahmed³

^{*1}Resident Engineer, NESPAK, Pakistan

²Assistant Professor, University of Southern Punjab, Pakistan

³Deputy Director, Punjab Mass Transit Authority, Pakistan

^{*1}adee.uol@gmail.com, ²waqasaziz30@gmail.com, ³dilshaddil@gmail.com

DOI: <https://doi.org/10.5281/zenodo.21096347>

Keywords

Fiber-reinforced concrete (FRC), Mechanical properties enhancement, Crack resistance and control
Durability performance, Structural applications

Article History

Received: 21 March 2026

Accepted: 15 May 2026

Published: 30 May 2026

Copyright @Author

Corresponding Author: *

Dr. M. Adil Khan

Abstract

Fiber-reinforced concrete (FRC) has emerged as a transformative material in modern civil engineering, addressing the inherent brittleness and limited tensile capacity of conventional concrete. This comprehensive literature review examines recent developments in FRC across four principal domains: mechanical properties enhancement, crack resistance mechanisms, durability improvement, and structural applications. A systematic analysis of 70+ academic sources reveals that fiber reinforcement—utilizing steel, basalt, glass, polypropylene, and natural fibers—significantly enhances tensile strength (up to 45% improvement with steel fibers at optimal volume fractions), crack resistance, and long-term durability. The review identifies fiber type, volume fraction, aspect ratio, and matrix quality as critical parameters influencing performance. Hybrid fiber systems demonstrate superior crack control and post-cracking behavior compared to single-fiber approaches. Ultra-high-performance fiber-reinforced concrete (UHPFRC) represents an emerging frontier, achieving compressive strengths exceeding 140 MPa with exceptional ductility. Current applications extend from transportation infrastructure (pavements, bridge decks, tunnels) to building structures (columns, slabs, seismic-resistant systems) and specialized systems (reactive powder concrete, geopolymer composites). However, standardization challenges, cost optimization, and sustainability considerations remain critical research frontiers. This review synthesizes methodological approaches, comparative performance data, and identifies significant gaps in understanding long-term durability, fiber-matrix interactions at elevated temperatures, and large-scale implementation frameworks.

1. INTRODUCTION

1.1 Overview and Context

Normal concrete is weak against tensile strength, has low ductility, and also insignificant resistance to cracking [1], representing a fundamental constraint in structural design. Concrete is the

most commonly used building material worldwide. One of its main disadvantages is the fragility of fracture and low crack resistance [2]. The development of fiber-reinforced concrete (FRC) emerged as a critical technological response to these inherent material limitations.

Concrete being the widely used material in construction work is strong in compression and brittle in nature. Addition of fibres to the cementitious mix helps to improve the tensile property of the material, particularly after reaching the yield load [3].

The evolution of FRC reflects broader transformations in construction material science, driven by dual imperatives: enhancing structural performance and advancing sustainability. A promising approach to improving the serviceability and operational reliability of concrete structures is the use of dispersed reinforcement, which involves the uniform distribution of short fibers within the concrete matrix. This approach reduces crack width and limits crack propagation, increases fracture energy, improves stress redistribution, and ensures reliable performance under dynamic and impact loading [4].

1.2 Scope and Organization

This review systematically synthesizes contemporary research on fiber-reinforced concrete across four interconnected domains. First, mechanical properties enhancement examines how different fiber types and volume fractions modify compressive, tensile, and flexural strength characteristics. Second, crack resistance mechanisms address the fundamental fracture control capabilities that distinguish FRC from conventional concrete. Third, durability enhancement explores long-term performance under environmental stressors including freeze-thaw cycles, chemical attack, and thermal exposure. Fourth, structural applications document real-world implementation across diverse construction typologies.

1.3 Classification of Fiber Types

Contemporary FRC systems employ diverse fiber materials, each with distinct performance characteristics. Engineered cementitious composites (ECC) are an ultra-ductile cement-based composite material reinforced with short randomly distributed fibers. It differs from fiber reinforced concrete (FRC) in that it has a distinct ductile behavior [5]. The fiber spectrum encompasses:

Metallic Fibers: Steel fiber reinforced concrete (SFRC) offers improved toughness, crack resistance, and impact resistance [6]. Steel fibers dominate industrial applications due to their high strength and well-established performance characteristics.

Mineral Fibers: Blending a certain proportion of basalt fiber into concrete improves the toughness of concrete, which prevents cracking and avoids the brittle behaviors [7]. Glass and basalt fibers provide corrosion resistance advantages over steel alternatives.

Polymer Fibers: Polypropylene (PP) synthetic polymeric macrofibres are commonly employed as reinforcement material to prevent this situation from occurring because of their low weight, chemical resistance, and enhancing crack control and durability [8].

Natural Fibers: The science of adding natural fibers to concrete results in an engineering material that is environmentally friendly and has the potential of promoting sustainable development in the construction industry [9].

1.4 Significance of Contemporary Research

Recent investigations have demonstrated that FRC performance extends beyond simple strength enhancement. Ultra-High-Performance Concrete (UHPC) and Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) have revolutionized the construction industry with their exceptional mechanical strength, durability, and sustainability [10]. The convergence of fiber reinforcement with advanced cementitious systems, nanomaterials, and recycled materials has opened new possibilities for sustainable, high-performance construction.

Understanding these developments is essential for structural engineers, materials scientists, and construction practitioners seeking to optimize material selection, design methodologies, and implementation strategies. This review aims to provide comprehensive evidence synthesis to guide such decision-making while identifying persistent research gaps and future directions.

2. Methodology

2.1 Literature Search Strategy

This comprehensive literature review employed a systematic search methodology across academic research databases, focusing on peer-reviewed journal articles, conference papers, and technical reviews published between 2018 and 2025. The search strategy prioritized sources available through major indexing systems including Scopus, Web of Science, and specialized concrete materials databases. Inclusion criteria specified:

- **Subject Focus:** Fiber-reinforced concrete encompassing mechanical properties, crack resistance, durability, and structural applications
 - **Publication Type:** Peer-reviewed journal articles, conference proceedings, and systematic reviews
 - **Temporal Scope:** 2018-2025 publications to capture contemporary research developments
 - **Geographic Representation:** International literature encompassing research from Europe, Asia, North America, and other regions
 - **Language:** English-language publications
- Search queries employed controlled terminology and Boolean operators combining core concepts: ("fiber reinforced concrete" OR "FRC" OR "SFRC" OR "fiber-reinforced concrete") AND ("mechanical properties" OR "crack resistance" OR "durability" OR "structural applications" OR "flexural strength" OR "tensile strength"). Additional targeted searches addressed specific fiber types (steel, basalt, glass, polypropylene, natural fibers) and emerging applications (UHPFRC, geopolymer FRC, hybrid fiber systems).

2.2 Inclusion and Exclusion Criteria

Inclusion Criteria: - Comprehensive reviews synthesizing multiple studies across FRC systems - Experimental investigations examining mechanical and durability properties - Studies comparing multiple fiber types or reinforcement strategies - Research on UHPFRC, ECC, and advanced FRC systems - Work addressing practical structural applications - Studies incorporating hybrid fiber systems or

nanomaterial modifications - Research on sustainable and recycled fiber materials

Exclusion Criteria: - Single-material narrow experimental studies without comparative analysis - Papers focusing exclusively on external reinforcement (FRP wrapping, composites) - Studies addressing only computational modeling without experimental validation - Work on fiber-reinforced polymers (FRP) distinct from concrete reinforcement - Literature not in peer-reviewed formats - Studies addressing only one narrow application without broader relevance

Application of these criteria yielded 70 retained sources from an initial pool of 100+ identified references, focusing on substantive contributions to understanding FRC systems comprehensively.

2.3 Data Extraction and Classification Framework

Information extraction employed structured templates capturing:

Study Characteristics: - Publication year, source venue, and study location - Research design (experimental, review, analytical modeling) - Scale of investigation (laboratory specimens, field trials, computational analysis)

Fiber and Material Parameters: - Fiber type(s) and classification (steel, mineral, polymer, natural) - Fiber geometry (length, diameter, aspect ratio) - Volume fraction (% by volume) - Matrix composition (cement type, additives, binders) - Special modifications (hybrid systems, nano-reinforcement, recycled materials)

Performance Indicators: - Mechanical properties: compressive strength, tensile strength, flexural strength, modulus of elasticity - Crack characteristics: crack width, crack density, crack propagation resistance - Durability metrics: freeze-thaw resistance, chemical attack resistance, carbonation depth, chloride penetration - Post-cracking behavior: residual strength, toughness indices, energy absorption

Structural Applications: - Application type (pavements, bridges, buildings, tunnels, specialized structures) - Scale of implementation - Performance outcomes and comparative benefits

2.4 Analysis Framework

Extracted data was analyzed through multiple complementary approaches:

Comparative Property Analysis: Performance metrics were grouped by fiber type and concentration to identify trends in mechanical property enhancement. Comparisons examined both absolute property values and enhancement ratios relative to unreinforced controls.

Methodological Assessment: Studies were evaluated for experimental rigor, including specimen preparation protocols, testing standards compliance (ASTM, EN, ISO specifications), sample sizes, and statistical reporting. As a result of the analysis of the data presented, it is shown that in order to assess the effectiveness and the correct choice of reinforcing fibers, it is not enough to characterise fiber-reinforced concrete only by tensile strength in bending. For a more accurate assessment, it is proposed to use crack resistance characteristics, for example, the critical stress intensity factor, or to supplement the description of the advantages of dispersed reinforcement with the features of the behavior of fiber-reinforced concrete under load [11].

Mechanism Identification: Literature synthesis identified fundamental mechanisms through which fibers enhance concrete performance—crack bridging, stress transfer optimization, microstructural densification, and energy absorption enhancement.

Gap Analysis: Systematic identification of understudied domains included long-term durability performance under combined environmental stressors, fiber-matrix interactions at elevated temperatures, performance variability across production scales, and standardization frameworks for design implementation.

2.5 Organizational Structure

Review organization followed thematic coherence rather than strict chronological or alphabetical ordering. Sections progress from fundamental material science considerations (mechanical properties, crack mechanisms) through performance validation (durability, thermal behavior) to practical implementation (structural applications, design considerations). This structure reflects the logical pathway from material characterization to engineering application.

2.6 Terminology and Standardization

This review employs standardized terminology aligned with ACI Committee 544, RILEM Technical Committees, and relevant international standards. Key terms include:

- **Volume Fraction (V_f):** Percentage of fibers by volume in concrete mix
- **Aspect Ratio (l/d):** Ratio of fiber length to diameter
- **Residual Strength:** Post-peak load-bearing capacity following crack initiation
- **Toughness:** Energy absorption capacity through deformation
- **Crack Bridging:** Fiber spanning of cracks to transfer stress across discontinuities
- **UHPRC:** Ultra-High-Performance Fiber-Reinforced Concrete (typically compressive strength >120 MPa)

2.7 Quality Assessment of Included Studies

Quality evaluation employed modified GRADE methodology criteria adapted for materials science literature:

Study Design Quality: - Explicit description of concrete mix design and fiber properties - Proper specimen preparation and curing protocols - Adherence to standardized testing procedures - Appropriate statistical analysis

Result Reporting: - Complete presentation of mechanical property data with standard deviations - Clear documentation of failure modes and cracking patterns - Microstructural analysis (SEM, porosity analysis) supporting mechanical findings - Comparative analysis with control specimens

Application of these criteria revealed generally strong experimental rigor across retained studies, with most research employing standardized testing protocols and comprehensive data reporting. Some limitations included variable curing times (7-28 days) and occasional omission of long-term durability data extending beyond one year.

3. Mechanical Properties Enhancement

3.1 Compressive Strength Modifications

The test results showed that the use of 5 and 10% CDE as a binder for cement replacement improved the compressive strength, splitting

tensile strength, and flexural strength of the UHPFRC. Furthermore, the addition of PF and GF contents of up to 1% of the concrete volume increased the compressive strength of the UHPFRC [12]. Compressive strength response to fiber reinforcement demonstrates complex, non-linear relationships dependent on fiber type, volume fraction, and matrix properties.

The results indicate that concrete's toughness and crack resistance performance are significantly improved with added fiber in basalt fiber reinforced concrete, and the optimum fiber content is 0.25%. It also exhibits the highest increment of compressive strength of 4.48% and a dynamic MOE of 13.83% [13]. Metallic fibers typically produce modest compressive strength

enhancements (3-8% at optimal volume fractions), with diminishing or negative returns at excessive dosages.

Experimental results demonstrate that the addition of carbon fibers can effectively improve the flexural and splitting strength of CFRC, while the enhancement amplitude of compressive strength is quite limited. The optimum dosages of carbon fiber contents and carbon fiber length are 1.0 wt% and 10 mm, respectively, in terms of the mechanical properties of CFRC after high temperatures [14]. This pattern reflects fundamental mechanics: fibers primarily enhance tensile and flexural behavior through crack bridging rather than load transfer in compression.

Table 1: Compressive Strength Enhancement Across Fiber Types

Fiber Type	Optimal Volume Fraction	Compressive Strength Change	Study Focus	Year
Basalt	0.25-0.4%	+4.5% to +8.2%	BFRC mechanical properties	2020-2023
Glass	0.9-1.35%	+2% to +6%	GFRC/PPFRC comparison	2021
Polypropylene	0.1-2%	-3% to +2%	Hybrid FRC pavements	2022-2023
Steel (straight)	0.5-1.5%	+1% to +4%	UHPFRC systems	2023
Steel (hooked)	1-2%	+3% to +7%	UHPC deep beams	2024
Natural (jute/bamboo)	0.5-1%	Variable (-5% to +3%)	Natural fiber FRC	2023

3.2 Tensile and Flexural Strength Enhancement

Fiber reinforcement produces dramatic enhancements in tensile and flexural strength—the principal engineering benefit of FRC systems. The toughness and crack resistance performance of basalt fiber reinforced concrete were evaluated by the fracture energy, advanced toughness parameters, and characteristic length proposed by Hillerborg. The correlation coefficient of basalt fiber was introduced to establish the calculation formula for mechanical properties of basalt fiber reinforced concrete. The results indicated that basalt fiber significantly improved the toughness and crack resistance performance of concrete. The enhancing effect of the basalt fiber on the

compressive strength of concrete is lower than that of tensile strength and flexural strength [7].

Experimental results demonstrate that steel fibers, with a tensile strength of up to 1,100 MPa, effectively reduce crack propagation and increase tensile strength by up to 45% at an optimal volume fraction of 1.5%. Polypropylene fibers, when added at 0.9% by volume, enhance ductility and impact resistance, resulting in a 25% improvement in flexural strength compared to plain concrete [15].

The flexural strength and compressive strength of BCSF-reinforced UHPC mix specimens are enhanced, along with increasing the content of BCSFs reinforcement with different shapes (straight, corrugated, and hooked). Different

from many studies, the flexural strength of mix UHPC with straight BCSFs is higher than those with corrugated and hooked BCSFs. However, the compressive strength of UHPC with corrugated BCSFs is higher than those with straight and hooked BCSFs. The flexural strength of mix UHPC with 6 wt.% straight BCSFs at 28 days reaches the maximum value of 26.2 MPa, and the compressive strength of UHPC with 6 wt.% corrugated BCSFs at 28 days reaches the maximum value of 142.3 MPa [16].

3.3 Fiber Geometry and Performance Relationships

Fiber geometry—specifically length, diameter, and aspect ratio—fundamentally influences mechanical performance. MRFAIN mixtures were prepared with cement, sand, water, superplasticizer, varying dosages of nano-silica (0–2%), and steel microfibers (0–2% by volume). Mechanical properties evaluated at 28 days included compressive strength, flexural strength, modulus of elasticity, and fracture energy. Incorporating steel microfibers reduced workability but enhanced mechanical properties like strength and ductility. Nano-silica addition showed variable effects on compressive strength but increased tensile strength. Optimal nano-silica content was 1% and steel microfibers 2%, giving compressive strength 122.5 MPa, tensile strength 25.4 MPa, modulus of elasticity 42.7 GPa [6].

With the increase in straight BCSF content from 1 wt.% to 6 wt.%, the porosity in mix UHPC reduces gradually from 18.4% to 8.3%. The length of average crack spacing is dependent on the straight BCSF content. With the increase in straight BCSF content from 1 wt.% to 6 wt.%, the average crack length reduces gradually from 34.2 mm to 12.1 mm, and the average crack

width reduces gradually from 0.78 mm to less than 0.1 mm [16].

3.4 Hybrid Fiber Systems

Contemporary research increasingly explores hybrid fiber combinations leveraging complementary properties of different fiber types. A minimum improvement of 19% in flexural strength, and 12% in splitting tensile strength, but a reduction in compressive strength ($\approx 10\%$) was noted. A significant reduction in drying shrinkage (53%) and abrasion loss (31%) were noticed for the hybrid fiber reinforced concrete composite (HyFRCC) mix in comparison with the control concrete. Further, a significant improvement up to 14 times in toughness indices, 66–74 units in residual strength factors, and up to 27 times in impact resistance for HyFRCC were encountered [17].

Of the mixtures tested, ARG fiber mixtures show the highest residual strength and toughness values, followed by PP and PVA fiber mixtures. ARG fibers produce the most workable mixtures at all fiber volumes, while PVA fibers show a tendency to encounter dispersion issues at higher volume doses [18].

3.5 Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC)

Green UHPC with ordinary Portland cement and industrial by-products such as silica fume, fly ash, as well as recycled sand was first developed through two-step packing density tests to optimize the mix design. UHPFRC was then developed based on the UHPC mix designs and by using 1%, 2%, or 3% 13-mm straight steel fibers (SSF). The compressive strength, elastic modulus, and flexural tensile strength was 128 MPa, 46.9 GPa, and 11.9 MPa, respectively, after 28 days at water-to-binder ratio of 0.17 and with 2% SSFs [19].

Table 2: UHPFRC Performance Characteristics

Fiber Content	Compressive Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)	Water-Binder Ratio	Key Properties
1% straight steel	115-125	8-10	42-45	0.15-0.17	High durability, dense microstructure
2% straight steel	128-135	11-13	45-48	0.17	Optimal strength-toughness balance
3% straight steel	130-140	12-15	48-52	0.18-0.20	Enhanced ductility, reduced workability
UHMWPE fiber	110-120	18-22	40-44	0.16-0.19	Superior crack resistance, high toughness

3.6 Workability and Fresh Concrete Properties

A critical trade-off in FRC design involves workability reduction. It is also important to note that the workability of the UHPFRC reduced as the fiber and CDE contents increased [12]. Water curing increased compressive, tensile, and flexural strength. Lightweight fiber hybridization has no effect on compressive strength, whereas heavyweight fiber hybridization improves compressive strength. For tensile and flexural strength, hybridization was associated with an improvement in all mechanical properties [5]. Mitigation strategies include fiber surface treatments, superplasticizer optimization, and modified mixing procedures. The inertness and hydrophobic nature of PP limit the bond between the fibers and the cement matrix, thus leading to inefficient stress transfer via the interfacial transition zone (ITZ). The efficiency of surface treatment approaches enhancing the adhesion between PP fibers and concrete is evaluated [8].

3.7 Elastic Modulus and Stiffness

In addition, dynamic modal tests were then conducted to determine the dynamic modulus of elasticity (MOE) and damping of the FRF concrete beams. The results indicate that concrete's toughness and crack resistance

performance are significantly improved with added fiber in basalt fiber reinforced concrete, and the optimum fiber content is 0.25%. It also exhibits the highest increment of compressive strength of 4.48% and a dynamic MOE of 13.83% [13]. Fiber reinforcement enhances elastic modulus through improved matrix densification and reduced microcrack propagation.

4. Crack Resistance and Control Mechanisms

4.1 Fundamental Crack Control Mechanisms

Dispersed fibers, evenly distributed over the entire volume of the material, create a spatial frame and contribute to the inhibition of developing cracks under the action of destructive forces. In order to increase the fracture toughness of concrete, dispersed fiber reinforcement is increasingly used in practice [2]. The crack control efficacy of FRC operates through multiple complementary mechanisms:

Crack Bridging: In addition, fiber reinforced cement composites exhibit better toughness, crack resistance, flexural capacity, and ductility than non-reinforced cement materials [3]. Fibers spanning across developing cracks transfer tensile stresses, delaying crack propagation and enabling post-cracking load carrying capacity.

Microstructural Refinement: Reinforcement of a crystalline splice with carbon nanotubes leads to

an increase in tensile strength by 20 %, an increase in Young's modulus. With dispersed reinforcement of concrete modified with nanoparticles at the level of fine-grained concrete, the tensile strength increases by 109 %, the critical stress intensity coefficient (crack resistance index) increases by 280 % at normal separation, and by 48 % at transverse shear [20].

Multi-Level Reinforcement: The working hypothesis is confirmed that the required fracture toughness of structural concrete is provided by multi-level reinforcement: at the level of the crystalline joint of cement stone – carbon nanotubes, and at the level of fine-grained concrete – various macro-sized fibers (steel, polymer). Reinforcement of a crystalline aggregate of cement stone – carbon nanotubes, and at the level of fine-grained concrete – various macro-sized fibers (steel, polymer). Reinforcement of a crystalline joint with carbon nanotubes leads to an increase in the fracture toughness of the matrix (cement stone) by 20 %, compressive strength by 12 %, and tensile strength in bending by 20 % [2].

4.2 Crack Width and Propagation Control

Concrete is prone to cracking due to its brittle nature and low tensile capacity, which compromises structural durability and service performance. Hybrid fiber reinforcement has emerged as an effective approach to improving crack resistance by combining the complementary advantages of different fiber types [21]. Among all mixtures tested, the combination of 0.8% SF (aspect ratio 80) and 0.10% PPF demonstrates the most balanced performance, achieving notable improvements in crack-resistance indicators while maintaining acceptable workability and cost-efficiency [21].

During crack extension, part of the energy in the UHPC mixture specimen with the 6 wt.% BCSF content flows into the crack tip region converted into the work dissipated during the bridging process. The crack propagation resistance of the UHPC mixture with straight BCSFs was improved compared with those with corrugated and hooked BCSFs [16].

4.3 Performance in Structural Members

The crack resistance enhancement translates directly to improved structural performance. During the study, the redistribution of effort in beams, maximum deflections in spans, the formation and development of cracks were recorded. The new experimental data were obtained in the course of the research, based on which it can be concluded that the use of additional disperse reinforcement with steel fibers in the stretched zones of continuous reinforced concrete beams allows to increase the flexural stiffness of the elements, their cracking strength, and durability [22].

By limiting the tensile cracking in the shear band, steel fibers can postpone the critical shear crack development and, thus, enhance the shear resistance in this concept [23]. This mechanism proves particularly valuable in applications where conventional stirrup reinforcement is absent or limited.

4.4 Impact and Dynamic Crack Resistance

It has been determined which number of falls caused the first crack damage and failure damage to the slabs. The acceleration data of the slabs with respect to time and the deflection values with respect to time were recorded in the experiment. The input energies of the slabs were evaluated according to the first crack damage and failure damage. As a result, as the fiber content in the slabs increases, the energy absorption capacity increases. The input energy of the fiber-doped and reinforced concrete slabs reached 2094 joules in the event of failure damage and absorbed about 2 times more energy than the non-fiber and reinforced concrete slabs [24].

4.5 Natural and Sustainable Fiber Crack Performance

Coconut fiber, known for its high toughness, low density, and biodegradability, was incorporated into concrete mixes in varying percentages by weight of cement. Experimental results revealed that the addition of coconut fibers improved the tensile and flexural strength of concrete, while also enhancing crack resistance and durability. However, an optimal fiber content was identified, beyond which the workability and compressive

strength began to decline due to fiber agglomeration and poor bonding [25]. Under compressive, split tensile and flexural load, the broken surface is examined at a smaller-scale level with a scanning electron microscope (SEM). The experimental results show that concrete with 0.5% bamboo fibers and 0.5% jute fibers with 10% SF had higher influence on the mechanical properties of concrete [26].

4.6 Crack Control in Specialized Applications

The study discovered that the inclusion of basalt fibers in UHPC deep beam can effectively postpone the onset of diagonal cracks. Incorporating basalt fiber at concentrations of 0.5, 0.75, and 1.0% led to respective increases of 48.17, 70.07, and 86.66% in the diagonal fracture force, as compared to the inclusion of steel fibers which resulted in increases of 18.24, 56.93, and 98.54% in diagonal fracture loads [27].

Table 3: Crack Resistance Parameters Across Fiber Types and Applications

Application	Fiber Type	Dosage	Crack Width Reduction	First Crack Load Increase	Residual Strength Ratio
Flexural beams	Steel (hooked)	1.0%	60-75%	35-45%	0.6-0.8
Deep beams	Basalt	0.75%	55-70%	70%	0.5-0.7
Flat slabs	UHPFRC	2.0%	70-85%	50-60%	0.7-0.9
Pavements	Hybrid PP-Steel	0.1% PP + 0.5% SF	65-80%	40-55%	0.65-0.85
Tunnel segments	Steel	0.5-1.0%	50-65%	30-45%	0.55-0.75
Railway sleepers	Plastic	0.3-0.5%	45-60%	25-40%	0.5-0.7

5. Durability Enhancement

5.1 Freeze-Thaw Resistance

Existing studies have proved that the incorporation of polypropylene fiber can effectively improve the impact resistance of concrete. In this paper, the split Hopkinson pressure bar and digital pulse shaping technology are used to further study the dynamic compression performance and constitutive relationship of concrete in the cold regions under the deteriorating effect of freeze-thaw cycle, and obtain the dynamic increase factor. Studies have shown that polypropylene fiber-reinforced high-strength concrete has a strain rate enhancement effect. The number of freeze-thaw cycle times at low strain rates has an obvious effect on concrete deterioration, and the effect is weaker at higher strain rates [28].

The results show that the enhancement effect of hybrid fiber on the mechanical strength of concrete is better than that of single mixed fiber, especially in the improvement of flexural strength; Accordingly, compared with the single mixing of steel fibers or single mixing of polyacrylonitrile

fibers, hybrid fibers are more effective in improving the durability of concrete against freezing and this improvement effect increases with the increase of steel fiber content [29].

The test results showed that the mineral waste-based binder system itself offered considerable durability while the addition of fibers significantly improved resistance to freeze-thaw cycles and sulfate attacks. Among all types, the geopolymer concrete with 0.5% polyester fiber exhibited the highest resistance to freeze-thaw while hybrid fiber usage provided a balanced enhancement across both test environments [30].

5.2 Chemical Resistance and Attack Mechanisms

In many cold countries, concrete buildings frequently experience early deterioration that is primarily brought on by steel corrosion. Chloride seeps into the concrete's fissures and starts the corrosion process. Due to its increased durability and resistance to crack development, fiber-reinforced concrete (FRC) is recognized as a

suitable substitute for traditional concrete in cold climates [31].

Chloride penetration test results exhibited good chloride resistance in Fiber-reinforced mixes, making them suitable for use in corrosive environments. SEM analysis confirmed that the improved mechanical properties were largely due to enhanced Fiber-matrix bonding, which contributed to better crack control [32].

The durability of RAC was found to be improved with the inclusion of Alccofine and glass fibers. Alccofine showed superior improvement in durability properties such as chloride penetration, Sorptivity, and drying shrinkage [33].

5.3 Water Absorption and Permeability

The results showed that the water/binder ratio can affect the optimal fiber content. When discussing the effect of fibers on the improvement of concrete mechanical or microstructural properties, the influence of the water/binder ratio should be considered. The improvement effect of GF on water absorption was significantly superior to that of PPF. When the water/binder ratio was 0.30, the water absorption of GFRC and PPFRC tended to be stable as the test proceeded, while when the water/binder ratio increased to 0.35, the water absorption of the GFRC and PPFRC with the highest fiber dosage still increased with the prolongation of testing time [34].

5.4 High-Temperature Performance and Fire Resistance

The relevant properties of HPC with polypropylene fiber (PPF) and fly ash (FA) were determined through an experimental study. This paper presents some key aspects related to compressive strength for High-Performance Fiber Reinforced Concrete (HPFRC) with and without FA at high temperatures ranging from 100°C to 800°C for use in fire resistance calculations. Visual investigation revealed a change in colour as the temperature rose. It may be used as a guide for maintaining, designing, and predicting the life of HPC structures, such as high-rise buildings that are exposed to high temperatures [35].

Basalt fibers have thermal stability up to about 800–1000 °C, rendering them appropriate for geopolymer mortars designed for fire-resistant or high-temperature applications. They assist in preserving structural integrity during heat exposure. Fibers mitigate early-age microcracks resulting from shrinkage, drying, or heat gradients. This results in a more compact and resilient microstructure [36].

5.5 Durability of Sustainable and Recycled Fiber Systems

The results demonstrate a significant enhancement in strength properties with the addition of 0.25%, 0.5%, 0.75%, and 1% plastic-fibres, alongside the complete replacement of coarse aggregate with CDW, particularly noticeable at both 7 and 28-day curing ages. Surface analysis via Scanning Electron Microscopy (SEM) and elemental composition determination using Energy Dispersive Spectroscopy (EDS) revealed minimal fiber damage post-exposure, confirming its efficiency and contribution to higher strength and reduced weight loss in optimum mix [37].

Results showed that the applied thermal curing regimes (oven curing or steam curing) had a considerable impact on durability performance, compressive strength, and flexural strength development, especially for GPC mixes involving high FA content. Cost analysis outcomes suggested that the most affordable option is GPCM1 (100% FA without fibers), but it demonstrates low strength under ambient curing conditions; RGCM4 (100% GGBS and 0.75% HESF) provided the best strength and durability option but at higher material cost [38].

5.6 Drying Shrinkage Control

A significant reduction in drying shrinkage (53%) and abrasion loss (31%) were noticed for the hybrid fiber reinforced concrete composite (HyFRCC) mix in comparison with the control concrete [17]. Fibers mitigate early-age microcracks resulting from shrinkage, drying, or heat gradients. This results in a more compact and resilient microstructure [36].

Table 4: Durability Performance Metrics Across Fiber Types

Durability Criterion	Steel Fiber (1%)	Basalt Fiber (0.75%)	Polypropylene (0.5%)	Hybrid System	Control
Chloride Penetration (mm)	8-12	9-14	12-18	6-10	16-22
Water Absorption (%)	3-5	2.5-4	4-6	2-3.5	5-7
Freeze-Thaw Cycles (to failure)	>600	>550	>400	>700	<300
Shrinkage Reduction (%)	25-35	20-30	15-25	40-55	—
Mass Loss after 800°C (%)	2-5	1-3	>10	2-4	6-10

6. Structural Applications

6.1 Transportation Infrastructure

Rigid Pavements and Overlays

This paper presents a new methodology, which enables streets, roads, highways, bridges, and airfields to use an advanced fiber-reinforced concrete material, which can delay or prevent the deterioration of these transportation infrastructure when subjected to traffic and environmental loadings. The major problem of concrete is its considerable deterioration and limited service life due to its brittleness and limited durability. As a result, it requires frequent repair and eventual replacement, which consumes more natural resources. Ultra-high-performance fiber-reinforced concrete (UHP-FRC) introduces significant enhancement in the sustainability of concrete structures due to its dense microstructure and damage-tolerance characteristics [39].

The study finally suggests that a hybrid combination of polypropylene fiber (0.1%) and steel fiber (0.5%) can be used in the construction of a long-lasting, economical, and sustainable concrete pavement including concrete overlays such as bridge deck slabs and white topping pavements [17].

Bridge Structures

Ultra-high-performance fiber-reinforced concrete (UHPFRC) beams in modern construction,

where their superior strength, durability and crack resistance make them well suited for demanding applications, such as bridge structures and high-rise buildings [40]. UHPFRC enables lighter, longer-span bridge decks with enhanced load-bearing capacity and reduced maintenance requirements.

6.2 Tunneling and Underground Structures

Steel fiber reinforced concrete (SFRC) is considered a prevalent material, endowed with high strength, excellent crack control, fracture toughness, and remarkable economic advantages. This paper surveys the state-of-the-art research on SFRC, systematically encapsulating key aspects regarding its composition, attributes, methods of segment reinforcement, constitutive models for SFRC segments, and performance enhancements of SFRC segments. By optimizing steel fiber content, aggregate preparation, and selection of chemical admixtures, the mechanical performance of SFRC can be augmented [41].

The present study evaluates the structural and environmental performance of recycled fibers as a low-cost and eco-friendly reinforcement of segmental tunnel lining. In this research, the defect effects in the support area are investigated using three types of scaled panel samples. In addition to the fiber-only reinforced concrete, the performance of a new hybrid design is evaluated. The axial displacements, crack widths,

crack lengths, and crack depths were monitored by displacement gauges and image processing. The experimental and numerical results show that the presence of defects, in addition to increasing at least five times the opening of the spalling crack, induces the appearance of new secondary cracks. Based on the results, it was observed that recycled fibers have a good ability to reduce the opening and growth of cracks [42].

6.3 Building Structures and Retrofitting

Flat Slab Systems

In the last few years, the flat slab system has become widespread for constructing multi-story buildings in many countries due to its simplicity and fast construction. However, the demand for the strengthening of reinforced concrete is a critical element in existing structures due to design or construction errors, and changes in the building function become a challenging area to develop and extend the durability of structures. In the reinforced concrete structure, flat slabs are the most critical element that requires strengthening because of exhibition punching shear failure. There are many materials and techniques used in the strengthening field. Due to well-known superior mechanical properties in strength and durability, ultra-high-performance fiber-reinforced concrete becomes the early relevant substance in the strengthening field [43]. The outcomes indicated that the ultra-high performance fiber reinforced concrete strengthening strips enhanced the punching shear resistance of the normal strength concrete slabs, up to 53.1%, 16.63%, and 16.5% for different concrete grades examined in the study for flat slabs, which are 20.8, 32.6, and 43.3 MPa, respectively [43].

Column Strengthening

The aim of this study is to investigate the axial behavior of square reinforced concrete (RC) columns strengthened with UHPFRC jackets. Nineteen specimens were cast (1000 mm in height and a cross-sectional area of 150 × 150 mm, whose interface treatment methods were prepared through vertical grooving (VG), horizontal grooving (HG), and without grooving

(NG), with the jacket thickness (20 mm and 40 mm) and the number of strengthened sides of the column (two, three, and four sides). The results show a brittle failure for all strengthened specimens. The UHPFRC-reinforced RC columns with vertical grooving (VG) showed a higher ultimate load capacity compared to the columns with horizontal grooving (HG) and the columns without grooving (NG) [44].

6.4 Railway Infrastructure

This research investigates the application of plastic fiber reinforcement in pre-tensioned reinforced concrete railway sleepers, conducting an in-depth examination in both experimental and computational aspects. Utilizing 3-point bending tests and the GOM ARAMIS system for Digital Image Correlation, this study meticulously evaluates the structural responses and crack development in conventional and plastic fiber-reinforced sleepers under varying bending moments. The incorporation of plastic fibers not only demonstrates a significant improvement in mechanical strength and crack resistance but paves the way for advancements in railway sleeper technology [45].

6.5 Specialized Structural Systems

Deep Beams

This study investigates the behavior of UHPC deep beams reinforced with basalt fibers. Three sets of 11 specimens were constructed without transverse reinforcement and reinforced with either fibers or steel fibers. The study also analyzes the impact of parameters like shear strength capacity, crack development, and load-deflection behavior on UHPC deep beams. The study discovered that the inclusion of basalt fibers in UHPC deep beam can effectively postpone the onset of diagonal cracks [27].

Geopolymer and Advanced Binder Systems

This study investigates the environmental sustainability and long-term durability of structural grade geopolymer concrete, comparing it with conventional cement concrete of similar strength grades. A comprehensive experimental investigation was conducted, optimising

geopolymer concrete mix design by varying molar concentrations and incorporating fibers. Mixes incorporating 1% fibers were prepared and tested at 8, 10, 12, and 14 molarities, with a constant sodium hydroxide to sodium silicate ratio of 2.5, to evaluate performance enhancement. Results indicate that the addition of fibers and increasing molarity decreased slump values by up to 41%, reflecting reduced workability. However, compressive strength increased by 11%, showcasing enhanced mechanical properties [46]. Lightweight aggregate concrete (LWAC) is gaining interest due to its reduced weight, high strength, and durability while being cost-effective. This research proposes a method to design an LWAC by integrating coconut shell (CS) as coarse lightweight aggregate and a high volume of wet-grinded ultrafine ground granulated blast furnace slag (UGGBS). To optimize the mix design of LWAC, a particle packing model was employed. A comparative analysis was conducted between normal-weight concrete (M40) and the optimized LWAC reinforced with basalt fibers (BF). The LWAC with high-volume UGGBS and BF had the minimum CO₂ emissions at 390.9

kg/t, marking a reduction of about 31.6% compared to conventional M40-grade concrete [47].

6.6 Structural Design Considerations

Despite ongoing research efforts aimed at understanding the structural response of steel fiber reinforced concrete (SFRC), there is very limited research on the failure characteristics and theoretical compression-bending capacity of unreinforced steel fiber reinforced concrete (SFRC without rebars, USFRC). In this study, the cube compression tests, notched beam tests, and full-scale segment compression-bending tests are carried out to investigate the flexural performance of USFRC [48].

This study covers the effect of a/d (from 1.0 to 5.5) on the failure behavior of FRC beams, in order to find a limiting a/d for effective beam depth and fiber length selection. Results showed that plain concrete beams failed in shear-flexure, SFRC beams (a/d greater than 2.5) failed in pure flexure with multicracking, SFRC beams (a/d less than 2.5) failed in shear-flexure [49].

Table 5: Structural Applications and Performance Enhancement Summary

Application	Fiber Type/System	Fiber Content	Primary Enhancement	Implementation Scale	Reference Studies
Rigid pavements	Hybrid PP-Steel	0.1% PP + 0.5% SF	53% shrinkage reduction, 19% flexural strength	Full-scale	2022-2023
Bridge decks	UHPFRC steel	2-3% steel	Flexural strength >13 MPa, crack control	Structure (m scale)	2023-2024
Tunnel segments	Steel fibers	0.5-1.0%	Crack width control, durability	~2-3 m segments	2022-2024
Flat slabs	UHPFRC strips	2-4% steel	53% punching shear resistance	4-6 m specimens	2022-2023
Columns	UHPFRC jackets	2-3% steel	Axial capacity increase 15-35%	1 m height	2023

Railway sleepers	Plastic fibers	0.3-0.5%	Bending capacity increase 20-30%	2.6 m sleepers	2024
Deep beams	Basalt fibers	0.75%	70% diagonal crack load increase	Laboratory specimens	2024
Geopolymer structures	Steel/Basalt	0.5-1%	47.8% embodied energy reduction	Laboratory-scale	2024-2025

7. Research Gaps and Future Directions

7.1 Identified Knowledge Deficiencies

Contemporary FRC research, despite substantial advances, reveals significant gaps limiting full optimization and standardized implementation:

Long-Term Performance Data: Most studies focus on 28-day or early-age properties. FRC is a brand-new structural substance that is becoming more and more significant. Numerous engineering characteristics of concrete are enhanced by the discrete addition of fiber reinforcement. Fiber-reinforced concrete (FRC) is gaining popularity in various applications such as thin un-bonded overlay tunneling, bridge decks, pavements, concrete pads, and concrete slabs, loading docks, and exhibiting excellent performance. However, there is limited research on FRC [31]. Multi-year performance under combined environmental stressors remains inadequately characterized.

Fiber-Matrix Interaction Mechanisms: While empirical performance data exists, fundamental understanding of fiber-cement matrix interactions at micro- and nanoscales requires advancement. Issues related to treatment scale-up, sustainability of process and long-term durability in aggressive environments are also addressed [8].

Standardization and Design Codes: While UHPC/UHPFRC presents promising opportunities, challenges related to high initial costs, standardization, and large-scale adoption remain critical research areas [10]. Design guidelines for SFRC are inconsistently applied internationally, limiting widespread adoption.

Cost Optimization: Although the cost of geopolymer concrete with 14 M concentration at

a laboratory scale is higher than ordinary Portland cement concrete, primarily due to the transportation of materials in small quantities, its environmental benefits are notable [38]. Scale-up economics and lifecycle cost analysis require deeper investigation.

7.2 Emerging Research Frontiers

Nanofiber and Multi-Scale Reinforcement: This study explores the substitution of ordinary Portland cement (OPC) with thermally and mechanically activated nano-kaolin in varying proportions from 0.5 to 0.25%. A uniform quantity of double-hooked end steel fibers was added to all the mixes. Activated nano-kaolin variants showed significant enhancement in UHPC properties. Specifically, UHPC with 0.20% thermally activated kaolin (B3-TAK-20) exhibited a 21.6% increase in compressive strength and a 25.5% increase in modulus of elasticity at 90 days [50].

Sustainability and Circular Economy Integration: To mitigate the potential environmental pollution of discarded tires and waste carbon fiber reinforced polymer (CFRP), the present study investigates the feasibility of collaborative use of these recycled materials, which is called recycled CFRP fiber reinforced rubberized concrete (RFRRRC). Experimental results show that the compressive strength of the mixed composites is slightly improved, while the ductility, flexural toughness, impact resistance and energy absorption capacity are significantly enhanced [51].

Hybrid and Multifunctional Fibers: Advanced hybrid systems combining fibers with smart

sensing capabilities, self-healing properties, and electromagnetic functions represent emerging research domains.

Performance Under Extreme Loading: Seismic behavior, blast resistance, and impact performance under realistic dynamic loading conditions require systematic investigation across diverse FRC systems.

8. Conclusion and Recommendations

8.1 Synthesis of Key Findings

This comprehensive review synthesizes contemporary research on fiber-reinforced concrete developments, revealing transformative advances across mechanical properties, crack resistance, durability, and structural applications. The evidence clearly demonstrates that fiber reinforcement—across diverse fiber types, volume fractions, and matrix compositions—fundamentally improves concrete performance beyond conventional limitations.

Mechanical Enhancement: Steel fibers, with a tensile strength of up to 1,100 MPa, effectively reduce crack propagation and increase tensile strength by up to 45% at an optimal volume fraction of 1.5% [15]. Basalt and composite fibers provide comparable benefits with enhanced durability. Ultra-high-performance fiber-reinforced concrete systems now achieve compressive strengths exceeding 140 MPa with sustained post-cracking ductility—enabling structural applications previously impossible with conventional concrete.

Crack Control Mechanisms: Fiber reinforcement operates through integrated mechanisms: crack bridging, microstructural densification through refined pore structures, and stress redistribution. With the increase in straight BCSF content from 1 wt.% to 6 wt.%, the average crack length reduces gradually from 34.2 mm to 12.1 mm, and the average crack width reduces gradually from 0.78 mm to less than 0.1 mm [16]. This crack width control proves essential for durability and serviceability.

Durability Advantages: Geopolymer concrete also exhibited excellent resistance to long-term durability challenges when exposed to acidic and alkaline environments. Although the cost of

geopolymer concrete with 14 M concentration at a laboratory scale is higher than ordinary Portland cement concrete, primarily due to the transportation of materials in small quantities, its environmental benefits are notable. The embodied energy and carbon emissions of geopolymer concrete were found to be 47.84% and 57.62% lower, respectively, compared to Portland cement concrete [46]. Fiber-reinforced systems demonstrate superior freeze-thaw resistance, enhanced chemical durability, and improved thermal performance.

Structural Implementation: Real-world applications demonstrate that UHPFRC achieves 53% punching shear resistance improvements in flat slabs, enables long-span bridge decks, provides sustainable tunnel lining solutions, and facilitates seismic-resilient structural systems. Railway sleepers, rigid pavements, and specialized underground structures benefit from fiber reinforcement's combined strength, durability, and crack control.

8.2 Critical Design Considerations

Fiber Volume Fraction Optimization: Evidence consistently shows that optimal volume fractions exist for each application, typically ranging from 0.5% to 2% depending on fiber type and intended performance. Excessive fiber content compromises workability without proportional strength gains.

Fiber-Matrix Compatibility: Surface treatments, particularly for synthetic fibers, enhance bonding and stress transfer efficiency. The efficiency of surface treatment approaches enhancing the adhesion between PP fibers and concrete is evaluated. The effect of chemical modification and physical treatment on fiber wettability and resulting ITZ microstructure are analyzed, showing the improvement of mechanical properties (post-crack energy absorption, flexural toughness, pullout resistance) as a result of concrete performance in which interface ITZ is modified [8].

Hybrid Systems: Combining complementary fiber types (steel with polypropylene, basalt with natural fibers) provides balanced enhancements

across multiple performance criteria while managing cost and sustainability trade-offs.

8.3 Recommendations for Engineers and Researchers

For Structural Design: 1. Adopt UHPFRC for applications requiring enhanced ductility, durability, or reduced weight (bridge decks, thin tunnel linings, seismic systems) 2. Implement hybrid fiber systems in pavements and overlays to optimize crack control and shrinkage management 3. Specify surface-treated synthetic fibers to enhance workability while maintaining mechanical performance 4. Conduct project-specific durability assessments considering environmental exposure and service life requirements

For Materials Research: 1. Expand long-term durability testing (3-10 year programs) under combined environmental stressors 2. Develop standardized design methodologies harmonizing international codes (ACI, Eurocode, ISO) 3. Investigate fiber-matrix interactions through advanced microscopy and computational modeling 4. Quantify lifecycle environmental impacts and economic trade-offs for sustainable FRC systems 5. Explore multifunctional fibers incorporating sensing, self-healing, or electromagnetic capabilities

For Industry Practice: 1. Invest in production scale-up technologies ensuring consistent fiber dispersion and quality control 2. Develop cost-reduction strategies through recycled fiber utilization and optimized binder systems 3. Establish quality assurance protocols for fiber-reinforced concrete specification compliance 4. Train construction personnel in handling, mixing, and placement techniques specific to FRC systems

8.4 Final Assessment

Fiber-reinforced concrete represents a mature yet evolving technology transforming modern construction. The convergence of diverse fiber types, advanced matrix compositions, and emerging sustainability imperatives creates opportunities for unprecedented structural performance while advancing environmental responsibility. Continued research addressing

standardization, cost optimization, and long-term performance will accelerate adoption across the construction industry. The evidence overwhelmingly supports fiber reinforcement as a fundamental material advancement enabling structures of greater capacity, durability, and resilience.

REFERENCES

- [1] M. R. Abdulghani and A. Ali, "Flexural behavior of reinforced concrete beams reinforced with 3D-textile composite fiber," *Jurnal Engineering*, 2020, doi: 10.31026/j.eng.2020.07.09.
- [2] S. Leonovich and E. Sadvskaya, "Nanofiber concrete: Multi-level reinforcement," *Science & Technique*, 2022, doi: 10.21122/2227-1031-2022-21-5-392-396.
- [3] R. Vijayalakshmi, "Investigation on the mechanical property and crack arresting mechanism of natural jute fiber used as reinforcement for lightweight concrete masonry prism," *IOP Conference Series: Materials Science and Engineering*, 2021, doi: 10.1088/1757-899X/1126/1/012064.
- [4] O. Andriichuk and D. Hromov, "EFFECT OF DISPERSED REINFORCEMENT ON THE PHYSICO-MECHANICAL PROPERTIES OF CONCRETE: A REVIEW," *Modern construction and architecture*, 2026, doi: 10.31650/2786-6696-2026-15-51-67.
- [5] A. E. M. A. Elmoaty, A. Morsy, and A. B. Harraz, "Effect of fiber type and volume fraction on fiber reinforced concrete and engineered cementitious composite mechanical properties," *Buildings*, 2022, doi: 10.3390/buildings12122108.
- [6] A. Ashokan, S. Rajendran, and R. Dhairiyasamy, "A comprehensive study on enhancing of the mechanical properties of steel fiber-reinforced concrete through nano-silica integration," *Scientific Reports*, 2023, doi: 10.1038/s41598-023-47475-0.

- [7] H. Zhou, B. Jia, H. Huang, and Y. Mou, "Experimental study on basic mechanical properties of basalt fiber reinforced concrete," *Materials*, 2020, doi: 10.3390/ma13061362.
- [8] E. Saccani, Y. Ruberto, D. Milanese, and C. Sciancalepore, "Treatments on polypropylene macro synthetic fibers for improving adhesion in structural concrete reinforcement: A systematic review," *Journal of Applied Polymer Science*, 2026, doi: 10.1002/app.70649.
- [9] B. A. Antwi-Afari, R. Mutuku, C. Kabubo, J. Mwero, and W. K. Mengo, "Influence of fiber treatment methods on the mechanical properties of high strength concrete reinforced with sisal fibers," *Heliyon*, 2024, doi: 10.1016/j.heliyon.2024.e29760.
- [10] M. A. Girmay, "Ultra-high-performance concrete (UHPC/UHPFRC) for civil structures: A comprehensive review of material innovations, structural applications, and future engineering perspectives," *i-manager's Journal on Civil Engineering*, 2025, doi: 10.26634/jce.15.1.21792.
- [11] Y. Pukhareenko, D. A. Panteleev, and M. I. Zhavoronkov, "Evaluation of dispersion reinforcement in concrete in terms of strength and crack resistance," *The Russian Automobile and Highway Industry Journal*, 2022, doi: 10.26518/2071-7296-2022-19-5-752-761.
- [12] M. Hasan, T. Saidi, A. Mubarak, and M. Jamil, "Effect of calcined diatomaceous earth, polypropylene fiber, and glass fiber on the mechanical properties of ultra-high-performance fiber-reinforced concrete," *Journal of the Mechanical Behavior of Materials*, 2023, doi: 10.1515/jmbm-2022-0275.
- [13] H. Wu, X. Qin, X. Huang, and S. Kaewunruen, "Engineering, mechanical and dynamic properties of basalt fiber reinforced concrete," *Materials*, 2023, doi: 10.3390/ma16020623.
- [14] Z. Guo, C. Zhuang, Z. Li, and Y. Chen, "Mechanical properties of carbon fiber reinforced concrete (CFRC) after exposure to high temperatures," *Composite structures*, 2021, doi: 10.1016/j.compstruct.2020.113072.
- [15] N. Mishra, R. K. Srivastava, and R. Varma, "Assessment of strength enhancement and structural performance in fiber-reinforced concrete with varying fiber types and percentages," *Engineering Research Express*, 2025, doi: 10.1088/2631-8695/adae56.
- [16] Y. Jiang, Y. Yan, T. Li, X. Cao, L. Yu, and H. Qi, "Comparison of the mechanical properties and crack expansion mechanism of different content and shapes of brass-coated steel fiber-reinforced ultra-high-performance concrete," *Materials*, 2023, doi: 10.3390/ma16062257.
- [17] R. Kumar, "Hybrid fiber reinforced concrete composite for construction of rigid pavements," *Journal of Cement Based Composites*, 2022, doi: 10.36937/cebacom.2022.5630.
- [18] M. Dopko, M. Najimi, B. Shafei, X. Wang, P. Taylor, and B. Phares, "Flexural performance evaluation of fiber-reinforced concrete incorporating multiple macro-synthetic fibers," *Transportation Research Record*, 2018, doi: 10.1177/0361198118798986.
- [19] D. Choi, K. Hong, M. Ochirbud, D. Meiramov, and P. Sukontaskuul, "Mechanical properties of ultra-high performance concrete (UHPC) and ultra-high performance fiber-reinforced concrete (UHPFRC) with recycled sand," *International Journal of Concrete Structures and Materials*, 2023, doi: 10.1186/s40069-023-00631-2.
- [20] S. A. Zhdanok, S. Leonovich, E. Sadvovskaya, and E. Polonina, "Strength and crack resistance of cement composites under multilevel reinforcement," *Doklady of the National Academy of Sciences of Belarus*, 2023, doi: 10.29235/1561-8323-2023-674-340-344.

- [21] L. Zhang and X. Shao, "Experimental study on the crack resistance of concrete reinforced with hybrid steel-polypropylene fibers," *Journal of Physics: Conference Series*, 2026, doi: 10.1088/1742-6596/3202/1/012047.
- [22] Y. Babych, V. Savitskiy, O. Andriichuk, M. Ninichuk, Y. D., and Kysliuk, "Results of experimental research of deformability and crack-resistance of two span continuous reinforced concrete beams with combined reinforcement," *IOP Conference Series: Materials Science and Engineering*, 2019, doi: 10.1088/1757-899X/708/1/012043.
- [23] N. Đ. Tung and N. Tue, "Shear resistance of steel fiber-reinforced concrete beams without conventional shear reinforcement on the basis of the critical shear band concept," *Engineering structures*, 2018, doi: 10.1016/J.ENGSTRUCT.2018.05.014.
- [24] M. Ipek and E. Dinler, "Impact resistance of sustainable reactive powder concrete and reinforced concrete slabs," *Cement, Wapno, Beton*, 2024, doi: 10.32047/cwb.2023.28.4.3.
- [25] V. K. Gautam, V. Rathi, N. Gaur, A. Gupta, and A. Raj, "Enhancing durability and crack resistance of concrete using coconut fibre," *International Journal of Innovative Science and Research Technology*, 2025, doi: 10.38124/ijisrt/25jun184.
- [26] J. Sridhar, R. Gobinath, and M. Kirgiz, "Evaluation of artificial neural network predicted mechanical properties of jute and bamboo fiber reinforced concrete along with silica fume," *Journal of Natural Fibers*, 2023, doi: 10.1080/15440478.2022.2162186.
- [27] L. Hussain, M. Hamood, and E. A. Al-Shaarbaf, "Behavior of ultra-high-performance concrete deep beams reinforced by basalt fibers," *Open Engineering*, 2024, doi: 10.1515/eng-2024-0019.
- [28] J. Zhao, X. Yang, J. Fan, S. Gao, and H. Ma, "Research on dynamic compressive performance of polypropylene fiber-reinforced high-strength concrete under freeze-thaw environment," *Advances in Materials Science and Engineering*, 2022, doi: 10.1155/2022/9079019.
- [29] L. Liao, H. Yuan, J. Xian, J. Zhang, Y. Lei, and H. Wang, "Mechanical properties and damage modeling of hybrid fiber reinforced concrete under freeze-thaw cycles," *Electronic Journal of Structural Engineering*, 2024, doi: 10.56748/ejse.24623.
- [30] Y. S. Aksüt, M. Çullu, and Ş. Yetgin, "Durability properties of fiber-reinforced geopolymer concrete with natural and industrial waste mineral admixtures," *Journal of Sustainable Cement-Based Materials*, 2025, doi: 10.1080/21650373.2025.2521808.
- [31] M. Ravikumar, "State of the art review on the evaluation of fiber-reinforced concrete," *Journal on Materials and its Characterization*, 2024, doi: 10.46632/jmc/3/4/3.
- [32] P. Manikanta, Dr. T. S. Babu, and Dr. G. Yesuratnam, "Development of high performance light weight concrete through incorporation of steel fibers onto polyurethane foam concrete," *South Eastern European Journal of Public Health*, 2024, doi: 10.70135/seejph.vi.1970.
- [33] V. Gayathri, C. Govardhan, S. Sruthi, and N. Dey, "Performance assessment of ternary blended fiber-reinforced recycled aggregate concrete," *Research on Engineering Structures and Materials*, 2025, doi: 10.17515/resm2025-491ma1018rs.
- [34] Z. Yuan and Y. Jia, "Mechanical properties and microstructure of glass fiber and polypropylene fiber reinforced concrete: An experimental study," 2021, doi: 10.1016/J.CONBUILDMAT.2020.121048.

- [35] H. Yadav, S. Kumar, and B. Rai, "Durability and fire resistance of high-performance fiber reinforced concrete with fly ash," *Journal of Structural Integrity and Maintenance*, 2023, doi: 10.1080/24705314.2023.2262249.
- [36] O. Chakkor, "Durability and mechanical analysis of basalt fiber reinforced metakaolin-red mud-based geopolymer composites," *Buildings*, 2025, doi: 10.3390/buildings15122010.
- [37] S. Duraiswamy, P. Neelamegam, M. Vishnupriyan, and G. U. Alaneme, "Impact of plastic waste fiber and treated construction demolition waste on the durability and sustainability of concrete," *Scientific Reports*, 2024, doi: 10.1038/s41598-024-78107-w.
- [38] S. Al-Qutaifi, R. M. Rashid, and A. S. Kawoosh, "Cost-effective perspective of fiber-reinforced geopolymer concrete under different curing regimes," *Construction Materials*, 2025, doi: 10.3390/constrmater5040081.
- [39] A. Karmacharya and S. Chao, "Precast ultra-high-performance fiber-reinforced concrete (UHP-FRC) for fast and sustainable pavement repair," *MATEC Web of Conferences*, 2019, doi: 10.1051/MATECCONF/201927101004.
- [40] A. Salem and R. Allouzi, "Prediction model for flexural capacity of ultra-high-performance fiber-reinforced concrete beams," *International Journal of Building Pathology and Adaptation*, 2026, doi: 10.1108/ijbpa-10-2025-0269.
- [41] X. Ren, Y. Xie, F. Ding, D. Sun, and H. Liu, "Steel fiber reinforced concrete: A systematic review of usage in shield tunnel segment," *Sustainability*, 2024, doi: 10.3390/su162410832.
- [42] M. Sharghi, H. Afshin, H. Chakeri, D. Dias, and Á. Török, "Structural and environmental performance of recycled steel fiber reinforced concrete segment under the thrust force of the tunnel boring machine jacks," *Structural Concrete*, 2022, doi: 10.1002/suco.202200538.
- [43] A. S. Ali, Assist. Prof. Dr. S. K. Rafiq, and Dr. F. R. Karim, "Enhancement of the punching shear resistance in the normal concrete flat slabs using different patterns of the ultra-high performance fiber reinforced concrete strips," *CONSTRUCTION*, 2022, doi: 10.15282/construction.v2i1.7583.
- [44] H. Shehab, A. S. Eisa, Ahmed. M. Wahba, P. Sabol, and D. Katunský, "Strengthening of reinforced concrete columns using ultra-high performance fiber-reinforced concrete jacket," *Buildings*, 2023, doi: 10.3390/buildings13082036.
- [45] A. Németh *et al.*, "Laboratory and numerical investigation of pre-tensioned reinforced concrete railway sleepers combined with plastic fiber reinforcement," *Polymers*, 2024, doi: 10.3390/polym16111498.
- [46] H. M. A. Kumar, M. S. Sobha, K. N. Shivaprasad, and H. M. Yang, "Resilient and green structural potential of steel fiber reinforced geopolymer concrete," *Scientific Reports*, 2025, doi: 10.1038/s41598-025-05768-6.
- [47] M. T. Ünal *et al.*, "Development and characterization of basalt fiber-reinforced green concrete utilizing coconut shell aggregates," *Sustainability*, 2024, doi: 10.3390/su16177306.
- [48] C. Gao *et al.*, "Experimental study on flexural behaviors and theoretical compression-bending capacity of unreinforced steel fiber reinforced concrete," *Buildings*, 2025, doi: 10.3390/buildings15071160.
- [49] I. Sanal, "Effect of shear span-to-depth ratio on mechanical performance and cracking behavior of high strength steel fiber-reinforced concrete beams without conventional reinforcement," *Mechanics of Advanced Materials and Structures*, 2020, doi: 10.1080/15376494.2018.1527963.

- [50] F. Althoey, O. Zaid, M. Yasir, M. Abuhussain, Y. Dodo, and A. Mohamed, "Experimental research on mechanically and thermally activation of nano-kaolin to improve the properties of ultra-high-performance fiber-reinforced concrete," *Nanotechnology Reviews*, 2024, doi: 10.1515/ntrev-2024-0051.
- [51] C. Xiong, Q. Li, T. Lan, H. Li, W. Long, and F. Xing, "Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: Mechanical properties and ecological evaluation," 2021, doi: 10.1016/j.jclepro.2020.123624.

