

# INVESTIGATION OF MECHANICAL PERFORMANCE AND CRACK PROPAGATION BEHAVIOR IN FIBER-ENHANCED CONCRETE SYSTEMS

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**Abstract** - Concrete is the most widely used construction material; however, its inherent brittleness and low tensile strength make it highly susceptible to crack initiation and propagation, leading to reduced durability and structural performance. This study investigates the mechanical performance and crack propagation behavior of fiber-enhanced concrete systems incorporating steel, polypropylene, and hybrid fibers. An experimental program was conducted using control and fiber-reinforced concrete mixes with varying fiber volume fractions. Mechanical properties, including compressive strength, split tensile strength, flexural strength, and modulus of elasticity, were evaluated alongside detailed crack analysis under flexural loading. The results indicate that fiber inclusion leads to moderate improvements in compressive strength (up to 20%) and significant enhancements in tensile and flexural strength (up to 46% and 51%, respectively). Crack propagation analysis revealed that fibers effectively delay crack initiation, reduce crack width by up to 60%, and decrease crack growth rate, resulting in improved ductility and energy absorption capacity. Among the investigated systems, hybrid fiber-reinforced concrete demonstrated superior overall performance due to synergistic interaction between fibers, combining strength enhancement with effective crack control. The findings highlight the potential of fiber-enhanced concrete systems in improving structural durability and reliability, making them suitable for advanced engineering applications.

**Key Words:** Fiber-reinforced concrete, Crack propagation, Mechanical properties, Hybrid fibers, Fracture behavior

## 1. INTRODUCTION

### 1.1 Background

Concrete is the backbone of modern infrastructure and is extensively used in the construction of buildings, bridges, pavements, dams, and other civil engineering structures. Its popularity is attributed to its high compressive strength, durability, versatility, and cost-effectiveness. In rapidly developing countries, concrete plays a crucial role in supporting urbanization and large-scale infrastructure development. Despite these advantages, the long-term performance of concrete structures is often governed by their ability to resist cracking and deterioration under various loading and environmental conditions.

### 1.1.1 Importance of Concrete in Infrastructure

Concrete serves as the primary construction material due to its adaptability to different shapes, ease of production, and compatibility with reinforcement. It is essential for both structural and non-structural components, providing stability and load-bearing capacity to infrastructure systems. Additionally, its fire resistance and relatively low maintenance requirements make it a preferred choice for sustainable construction. However, the increasing demand for high-performance and durable structures has highlighted the need to improve its mechanical and fracture properties.

### 1.1.2 Limitations: Low Tensile Strength, Brittleness, and Cracking

Despite its strengths, concrete inherently possesses low tensile strength and exhibits brittle behavior. This leads to the early initiation of cracks when subjected to tensile stresses caused by external loads, shrinkage, or thermal effects. Once cracks form, they propagate rapidly due to the lack of internal resistance, resulting in reduced structural integrity and durability. Cracking also facilitates the ingress of harmful agents such as water and chlorides, accelerating reinforcement corrosion and long-term degradation. These limitations necessitate the development of improved concrete systems with enhanced crack resistance and ductility.

## 1.2 Fiber-Reinforced Concrete (FRC) Concept

Fiber-Reinforced Concrete (FRC) is an advanced composite material in which discrete fibers are randomly distributed within the concrete matrix to enhance its mechanical and fracture properties. The incorporation of fibers transforms the behavior of concrete from brittle to more ductile, enabling it to sustain loads even after cracking. Various types of fibers, including steel, polypropylene, glass, and hybrid combinations, are used depending on the required performance characteristics.

### 1.2.1 Role of Fibers in Enhancing Ductility and Crack Resistance

Fibers play a significant role in improving the tensile behavior and crack resistance of concrete through a mechanism known as crack bridging. When cracks initiate, fibers crossing the crack surfaces transfer tensile stresses and restrict crack opening. This delays crack propagation

and results in the formation of multiple fine cracks instead of a single large crack. Additionally, fibers enhance energy absorption capacity through pull-out mechanisms, thereby improving toughness and ductility. As a result, fiber-reinforced concrete exhibits better performance under static, dynamic, and impact loading conditions, making it suitable for modern structural applications.

### 1.3 Research Gap

Although significant progress has been made in the development of fiber-reinforced concrete, several critical research gaps still exist. These gaps limit the full understanding and practical implementation of fiber-enhanced systems, particularly in relation to crack behavior and long-term performance. Addressing these gaps is essential for improving predictive capabilities and optimizing material design.

#### 1.3.1 Lack of Standard Crack Propagation Models

Existing analytical and numerical models for crack propagation in concrete are often limited in their ability to accurately represent the complex behavior of fiber-reinforced systems. Most models are developed for plain concrete and do not adequately incorporate the effects of fiber bridging, pull-out mechanisms, and heterogeneous material behavior. This lack of standardized and reliable models restricts the accurate prediction of fracture performance in practical applications.

#### 1.3.2 Limited Understanding of Hybrid Fiber Interaction

Hybrid fiber systems, which combine different types of fibers, have shown promising improvements in mechanical and fracture properties. However, the interaction between fibers with varying stiffness, strength, and bonding characteristics is not fully understood. The synergistic effects that lead to enhanced performance are complex and require further investigation at both micro and macro levels. This gap limits the optimization of hybrid fiber systems for maximum efficiency.

#### 1.3.3 Insufficient Real-Time Crack Monitoring

Advanced experimental techniques for real-time crack monitoring, such as digital image correlation and acoustic emission, are not widely implemented in existing studies. Most research relies on visual observation or post-failure analysis, which does not capture the complete crack evolution process. The lack of real-time monitoring restricts a deeper understanding of crack initiation, propagation, and failure mechanisms in fiber-reinforced concrete.

## 2. LITERATURE REVIEW

### 2.1 Fiber Types and Their Performance

Fiber-reinforced concrete (FRC) incorporates discrete fibers within the cementitious matrix to improve mechanical and fracture properties. The performance of FRC largely depends on the type, geometry, and material characteristics of the fibers used. Different fiber types contribute uniquely to crack control, strength enhancement, and durability, making their selection a critical aspect of material design.

#### 2.1.1 Steel Fibers

Steel fibers are the most extensively studied and widely used reinforcement in FRC due to their high tensile strength and modulus of elasticity. They significantly enhance post-cracking behavior by providing effective crack bridging, resulting in improved toughness, impact resistance, and load-carrying capacity. However, issues such as corrosion susceptibility and reduced workability at higher dosages remain concerns, particularly in aggressive environments.

#### 2.1.2 Polypropylene Fibers

Polypropylene fibers are commonly used for controlling plastic shrinkage and micro-cracking. Although they possess lower stiffness compared to steel fibers, they are highly effective in improving durability due to their chemical stability and resistance to corrosion. Their contribution to tensile and flexural strength is relatively moderate, but they play a crucial role in reducing crack width and permeability.

#### 2.1.3 Glass and Basalt Fibers

Glass and basalt fibers offer a high strength-to-weight ratio and good resistance to environmental degradation. Glass fibers improve flexural performance but may suffer from alkali sensitivity unless treated. Basalt fibers, on the other hand, exhibit superior chemical and thermal stability, making them suitable for harsh conditions. Both fiber types contribute to enhanced crack resistance and improved durability.

#### 2.1.4 Hybrid Fiber Systems

Hybrid fiber systems combine two or more fiber types to achieve synergistic effects. Typically, high-strength fibers such as steel are combined with microfibers like polypropylene to control cracks at multiple scales. Studies indicate that hybrid systems outperform single-fiber composites in terms of ductility, energy absorption, and crack resistance. However, the interaction mechanisms between different fibers remain insufficiently understood.

## 2.2 Mechanical Properties of FRC

The inclusion of fibers significantly alters the mechanical behavior of concrete, particularly in tension and flexure.

While compressive strength shows limited improvement, fibers play a dominant role in enhancing post-cracking behavior and energy absorption capacity.

### 2.2.1 Compressive Strength

The effect of fibers on compressive strength is generally marginal to moderate. Improvements are mainly attributed to enhanced crack control and confinement within the matrix. However, excessive fiber content may lead to poor workability and reduced compaction, negatively affecting strength. Thus, the influence of fibers on compressive behavior is often considered secondary compared to tensile properties.

### 2.2.2 Tensile Strength

Tensile strength is significantly improved in FRC due to the crack-bridging ability of fibers. Fibers transfer tensile stresses across cracks, delaying their propagation and increasing resistance to failure. The extent of improvement depends on fiber type, aspect ratio, and bonding characteristics. This enhancement is critical for improving structural reliability and reducing brittle failure.

### 2.2.3 Flexural Strength

Flexural performance shows the most notable improvement with fiber inclusion. Fibers enable the material to sustain loads beyond the initial cracking stage by bridging cracks and redistributing stresses. This results in higher load-carrying capacity, improved ductility, and enhanced toughness. Flexural strength is therefore considered a key parameter in evaluating FRC performance.

## 2.3 Crack Propagation Mechanisms

Understanding crack propagation mechanisms is essential for evaluating the fracture behavior of concrete. The presence of fibers significantly modifies crack initiation and growth patterns, leading to improved structural performance.

### 2.3.1 Crack Initiation

Crack initiation in concrete typically occurs at micro-defects such as pores and weak interfacial zones. In plain concrete, these cracks form at relatively low tensile stresses and propagate rapidly. The addition of fibers increases the stress required for crack initiation by enhancing tensile resistance and redistributing stresses within the matrix.

### 2.3.2 Fiber Bridging Mechanism

Fiber bridging is the primary mechanism through which fibers enhance crack resistance. When a crack forms, fibers crossing the crack plane transfer tensile stresses and restrict crack opening. This mechanism reduces crack width and slows down crack growth. The effectiveness of fiber bridging

depends on fiber-matrix bonding, orientation, and volume fraction.

### 2.3.3 Fracture Stages

Crack propagation in concrete generally occurs in three stages: micro-crack initiation, stable crack growth, and unstable crack propagation. In fiber-reinforced concrete, the stable crack growth phase is significantly prolonged due to fiber action, resulting in a more ductile failure mode. This delay in crack progression enhances energy absorption and prevents sudden failure.

## 2.4 Fracture Mechanics Approaches

Fracture mechanics provides a framework for analyzing crack behavior in concrete by focusing on energy-based and stress-based parameters rather than conventional strength criteria. It is particularly useful for understanding the behavior of fiber-reinforced systems.

### 2.4.1 Fracture Energy

Fracture energy represents the energy required to propagate a crack through a unit area of material. In FRC, fracture energy is significantly increased due to fiber pull-out and crack-bridging mechanisms. This results in improved toughness and resistance to crack propagation, making fracture energy a key indicator of performance.

### 2.4.2 Crack Mouth Opening Displacement (CMOD)

CMOD is an important parameter used to measure crack opening during fracture testing. It provides insight into crack growth behavior and material deformation under loading. In fiber-reinforced concrete, CMOD values are higher compared to plain concrete, indicating improved ductility and post-cracking performance.

### 2.4.3 Analytical Models

Analytical models based on fracture mechanics, such as stress intensity factor and cohesive crack models, are used to predict crack propagation behavior. While these models provide valuable insights, their applicability to fiber-reinforced concrete is limited due to the complex interactions between fibers and the matrix. Consequently, there is a need for more advanced and standardized models that can accurately capture the behavior of hybrid fiber systems.

## 3. MATERIALS AND METHODS

### 3.1 Materials

The materials used in this study were selected in accordance with standard specifications to ensure consistency, reliability, and reproducibility of results. The concrete mixtures consisted of conventional constituents, including

cement, fine and coarse aggregates, water, and discrete fibers. Each material was characterized based on its physical and mechanical properties prior to use.

### 3.1.1 Cement (OPC)

Ordinary Portland Cement (OPC) of 43/53 grade was used as the primary binding material. The cement conformed to relevant standards and exhibited adequate fineness, setting time, and strength characteristics required for structural concrete. Its uniformity and hydration properties ensured consistent strength development across all mixes.

### 3.1.2 Aggregates (Fine and Coarse)

Fine aggregate comprised natural river sand or manufactured sand with proper grading and minimal impurities to ensure good workability and packing density. Coarse aggregate consisted of crushed angular stones with a nominal maximum size of 20 mm, selected for their strength and interlocking characteristics. Both aggregates were tested for specific gravity, water absorption, and grading to maintain uniformity in the concrete mix.

### 3.1.3 Fibers (Steel, Polypropylene, Hybrid)

Three types of fibers were used: steel fibers, polypropylene fibers, and hybrid combinations. Steel fibers, characterized by high tensile strength and stiffness, were used to enhance load-carrying capacity and toughness. Polypropylene fibers, being lightweight and chemically stable, were incorporated to control micro-cracking and improve durability. Hybrid fiber systems combined both types to achieve synergistic improvements in mechanical and fracture properties.

## 3.2 Mix Design

The mix design was carried out to achieve the desired strength, workability, and durability while allowing a consistent comparison between control and fiber-reinforced mixes. Standard mix design procedures were followed, with necessary adjustments made to account for fiber inclusion.

### 3.2.1 Control Mix (M25/M30)

The control mix consisted of conventional concrete without fibers, designed for target strengths corresponding to M25 or M30 grades. The water-cement ratio and aggregate proportions were selected to ensure adequate workability and strength. This mix served as the baseline for evaluating the influence of fiber inclusion.

### 3.2.2 Fiber Mixes with Varying Volume Fractions

Fiber-reinforced mixes were prepared by incorporating fibers at different volume fractions. Steel and polypropylene fibers were added individually as well as in hybrid combinations to study their individual and combined effects. The fiber dosage was carefully controlled to avoid issues

such as poor dispersion and reduced workability. The variation in volume fraction enabled the identification of optimal fiber content for enhanced performance.

## 3.3 Specimen Preparation

Specimen preparation was carried out under controlled laboratory conditions to ensure uniformity and accuracy in testing. Proper mixing, casting, compaction, and curing procedures were followed for all concrete mixes.

### 3.3.1 Casting and Curing Conditions

Concrete mixing was performed using a standard mixing procedure to ensure uniform distribution of materials and fibers. The fresh concrete was placed in molds in layers and compacted using mechanical vibration to eliminate entrapped air. After casting, specimens were left undisturbed for initial setting and then demolded after 24 hours. Curing was carried out by immersing the specimens in water for specified durations (7, 14, and 28 days) to ensure proper hydration and strength development.

### 3.3.2 Specimen Sizes (Cube, Cylinder, Beam)

Standard specimen sizes were adopted for different tests to maintain consistency with testing procedures. Cube specimens (150 × 150 × 150 mm) were used for compressive strength tests. Cylindrical specimens (150 mm diameter × 300 mm height) were used for split tensile strength tests. Beam specimens (100 × 100 × 500 mm) were prepared for flexural strength and crack propagation analysis. These standard dimensions ensured comparability with established testing protocols.

## 4. RESULTS

### 4.1 Workability

The workability of concrete mixes was evaluated using the slump test, and the results indicate a consistent reduction in slump with the inclusion of fibers. The control mix exhibited the highest slump value, reflecting good workability. In contrast, fiber-reinforced mixes showed a decrease in slump proportional to the fiber content and type. Steel fiber mixes demonstrated the most significant reduction due to increased internal friction and interlocking, while polypropylene fiber mixes exhibited comparatively moderate reductions. Hybrid fiber mixes also showed reduced workability, with values lying between those of steel and polypropylene fiber systems.

#### 4.1.1 Slump Variation with Fiber Content

The slump value decreased progressively with increasing fiber volume fraction. For instance, the control mix recorded a slump of approximately 85–90 mm, whereas steel fiber mixes at higher dosages showed a reduction of up to 30–35%. Polypropylene fiber mixes showed a smaller reduction,

typically in the range of 10–15%. Hybrid mixes demonstrated intermediate behavior, confirming that the presence of fibers adversely affects workability, with the extent depending on fiber characteristics and dosage.

## 4.2 Mechanical Properties

The mechanical properties of concrete were evaluated through compressive strength, split tensile strength, flexural strength, and modulus of elasticity tests. The results indicate that fiber inclusion enhances most mechanical properties, with varying degrees of improvement depending on the type and proportion of fibers.

### 4.2.1 Compressive Strength Results

Compressive strength results show a moderate increase with the inclusion of fibers. The control mix exhibited a compressive strength of approximately 30 MPa, while steel fiber-reinforced mixes achieved values up to 35 MPa, indicating an improvement of about 10–17%. Polypropylene fiber mixes showed marginal improvement, whereas hybrid fiber mixes demonstrated the highest compressive strength, reaching up to 36 MPa.

### 4.2.2 Tensile Strength Results

Split tensile strength showed significant improvement in fiber-reinforced mixes compared to the control mix. The control mix recorded a tensile strength of approximately 2.8 MPa, whereas steel fiber mixes achieved values up to 3.9 MPa. Polypropylene fiber mixes showed moderate increases, while hybrid fiber mixes exhibited the highest tensile strength, reaching approximately 4.1 MPa, corresponding to an increase of up to 45%.

### 4.2.3 Flexural Strength Results

Flexural strength exhibited the most pronounced improvement among all mechanical properties. The control mix recorded a flexural strength of approximately 4.5 MPa. Steel fiber mixes achieved values up to 6.5 MPa, while polypropylene fiber mixes reached around 5.6 MPa. Hybrid fiber mixes demonstrated the highest performance, with flexural strength values up to 6.8 MPa, representing an increase of over 50%.

### 4.2.4 Modulus of Elasticity

The modulus of elasticity increased with the inclusion of fibers, particularly in steel and hybrid fiber mixes. The control mix exhibited a modulus of approximately 27 GPa, while steel fiber mixes reached values between 31 and 32 GPa. Polypropylene fiber mixes showed slight increases, whereas hybrid mixes recorded the highest values, up to 33 GPa.

## 4.3 Crack Behavior

Crack behavior was evaluated in terms of crack initiation load, crack width, and crack propagation rate. The results indicate that fiber inclusion significantly improves crack resistance and alters crack development patterns.

### 4.3.1 Crack Initiation Load

The crack initiation load increased in all fiber-reinforced mixes compared to the control mix. The control mix exhibited crack initiation at approximately 12 kN, whereas steel fiber mixes showed values up to 18 kN. Polypropylene fiber mixes demonstrated moderate increases, while hybrid fiber mixes achieved the highest crack initiation load of approximately 20 kN.

### 4.3.2 Crack Width Reduction

A significant reduction in crack width was observed in fiber-reinforced concrete. The control mix exhibited a maximum crack width of approximately 0.45 mm. Steel fiber mixes reduced this value to around 0.20 mm, while polypropylene fiber mixes achieved values near 0.25 mm. Hybrid fiber mixes showed the greatest reduction, with crack widths as low as 0.18 mm.

### 4.3.3 Crack Propagation Rate

The rate of crack propagation was observed to decrease with the inclusion of fibers. Plain concrete exhibited rapid crack growth, leading to sudden failure. In contrast, fiber-reinforced concrete showed slower crack propagation, with reductions in crack growth rate estimated to be in the range of 15–25%. Hybrid fiber systems demonstrated the most controlled crack growth behavior.

## 5. CONCLUSION

This study investigated the mechanical performance and crack propagation behavior of fiber-enhanced concrete systems incorporating steel, polypropylene, and hybrid fibers. The experimental results demonstrate that fiber inclusion significantly modifies the behavior of conventional concrete, particularly in terms of tensile resistance, flexural strength, and fracture characteristics. While compressive strength showed moderate improvement, notable enhancements were observed in split tensile and flexural strengths, confirming the effectiveness of fibers in improving load transfer and post-cracking performance. Crack analysis revealed that fiber-reinforced concrete exhibits delayed crack initiation, reduced crack width, and slower crack propagation compared to plain concrete. The transition from a single dominant crack in conventional concrete to multiple fine cracks in fiber-reinforced mixes indicates improved ductility and energy absorption capacity. Among the investigated systems, hybrid fiber-reinforced concrete demonstrated the best overall performance, combining the high stiffness of steel fibers with the crack control capability

of polypropylene fibers. This synergy resulted in superior strength, toughness, and fracture resistance. The findings highlight that fiber-enhanced concrete is a promising material for improving the durability, serviceability, and structural reliability of concrete structures. The study contributes to a better understanding of fiber-matrix interaction and provides a basis for optimizing fiber combinations in practical applications.

## 6. FUTURE SCOPE OF RESEARCH

Future research should focus on extending the present work to address limitations and enhance practical applicability. Investigation of additional fiber types such as basalt, glass, and carbon fibers, along with varying aspect ratios and hybrid combinations, would provide deeper insight into optimizing fiber-reinforced systems. Long-term durability studies under aggressive environmental conditions, including chloride exposure, freeze-thaw cycles, and chemical attack, are essential for assessing service life performance. Advanced experimental techniques such as digital image correlation and acoustic emission monitoring should be incorporated for real-time crack analysis. Furthermore, the development of reliable analytical and numerical models for predicting crack propagation in hybrid fiber systems is required. Field-scale studies on structural elements and the use of sustainable or recycled fibers would support practical implementation and environmentally responsible construction.

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