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A REVIEW OF THE INFLUENCE OF FIBER REINFORCEMENT ON CRACK PROPAGATION IN CONCRETE

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ABSTRACT

Fiber-reinforced concrete is gaining considerable attention as an effective way of controlling crack formation and improving post-cracking properties of concrete. The current paper focuses on the effects of the fiber reinforcement on the initiation of cracks, micro-crack formation, propagation and fracturing behaviour. An integrative literature review method has been used to evaluate the influence of such factors as the fiber type (steel, polypropylene, PVA, basalt, glass, natural and hybrid fibers), fiber bridging, pull-out and rupture mechanisms on the crack formation. Besides, the effect of fiber dosage, fiber length, fiber aspect ratio, fiber orientation, fiber distribution and fiber-matrix bonding on the crack control have been investigated. Different test methods, including bending and tensile tests, CMOD, DIC, AE, SEM, X-ray CT, fracture mechanics and numerical/mesoscale modelling have been used in the analyzed articles to assess crack behaviour. The analyzed literature shows that proper fiber reinforcement limits the crack opening, delays the crack propagation and improves fracture toughness, energy dissipation and post-cracking strength but depends considerably on fiber properties and fiber distribution. Practical applications of fiber reinforcement in the structures, pavement, industrial floors, tunnel lining, precast concrete, repair works and ultra-high-performance fiber-reinforced concretes (UHPC/UHPFRC) prove the potential of the technique. However, such issues as workability, fiber orientation, dispersion and scale effects require further research.

Keywords: *Fiber-Reinforced Concrete; Crack Propagation; Fiber Bridging; Fracture Behaviour; Crack Control; Post-Cracking Performance.*

1. INTRODUCTION

The use of concrete in the construction industry is among the most common because of its compressive strength, durability, versatility and economical features. However, due to the lack of tensile strength, this material is highly prone to cracking [1]. The reasons for cracking include drying and plastic shrinkage, thermal stresses, loading, creep, settlement, and other environmental factors. In the initial stage, such cracks usually occur as microcracks that appear in the cement paste and interfacial transition zone; however, further development and merging of these cracks results in their increasing size. Such development of cracks negatively impacts on strength, rigidity of concrete, as well as promotes the process of reinforcement corrosion.

Figure 1: Concrete [2]

Fiber reinforcement has been adopted as one of the most efficient techniques for crack control in concrete structures. Fibers of various types – from steel fibers, polypropylene fibers, polyvinyl alcohol fibers, basalt, glass, and synthetic fibers – can be added to the concrete matrix to enhance its crack and post-crack resistance. Fibers placed randomly in the matrix will serve to bridge the developing cracks and transfer the tensile stresses between the crack faces, which will limit crack opening and retard the process of crack propagation [3]. There are various criteria that define the efficiency of fiber reinforcement technique, including the type of fibers, their content, length, aspect ratio, orientation, distribution, and interface bonding.

However, there are many scientific works related to fiber-reinforced concrete; still, the results about the effect of fibers on crack propagation are scattered among various types of fibers, concrete mix and tests. Thus, there is a need for a systematic investigation of the way how fibers affect crack initiation, bridging, propagation and fracture. This literature review aims at analyzing the effect of various properties of fibers on the process of crack propagation in concrete [4]. Furthermore, it will also discuss the main principles of crack controlling with the use of fibers, the common methods of experimental and numerical investigation of this problem, and the main problems to be solved in the future.

2. REVIEW METHODOLOGY

Integrative literature review approach was used to study the effects of fiber on crack propagation in concrete [5]. Various relevant studies were critically evaluated based on the initiation, propagation, bridging, pull out and rupturing of fibers and the effects of fiber type, content, orientation, distribution and fiber-matrix interaction. Experimental approaches such as bend tests, tensile tests, CMOD test, DIC, Acoustic emission, Scanning Electron Microscope (SEM) and X-ray CT, along with fracture mechanics and modeling have been taken into consideration. The existing literature was analyzed for its key contributions and limitations in the field.

3. CRACK PROPAGATION MECHANISMS IN CONCRETE

Concrete is a composite and brittle material, which has a tendency to crack due to its low tensile strength. These cracks usually initiate as micro-cracks within the cement paste or between the paste-aggregate interface and can extend into larger cracks as a result of external loads [6].

- **Crack Initiation and Microcrack Development:** Cracks can originate as a result of shrinkage, temperature variations, applied loads, creep and defect presence. First, micro-cracks appear near porosities, aggregates and weak interfaces. As the stress increases, the microcracks become larger and interact with each other, eventually weakening the concrete.
- **Propagation and Coalescence of Cracks:** When the applied stress is higher than tensile strength of concrete, micro-cracks will start to propagate. A group of micro-cracks can unite to form one major macro-crack. The speed and orientation of the crack growth will be determined by the strength of the concrete, aggregates, loads and defects.
- **Zone of Fracture Process:** Fracture process zone is the damage area formed around the developing crack. Micro-cracks, branching cracks and the interaction between aggregate and paste take place within this region, dissipating fracture energy. Fiber reinforced concrete has fibers in this region to resist crack propagation.
- **Factors Affecting Crack Growth:** Factors that affect crack propagation include water-cement ratio, strength of concrete, aggregate size, type and properties, porosity, curing method, loading rate and temperature. In fiber reinforced concrete, fiber properties such as type, volume fraction, aspect ratio, orientation and bonding between fibers and matrix are also significant [7].
- **Plain Concrete vs. Fiber-Reinforced Concrete:** In plain concrete, once a critical crack occurs, it propagates rapidly, leading to brittle failure. In fiber reinforced concrete, fibers that bridge a crack carry the tensile stresses through it.

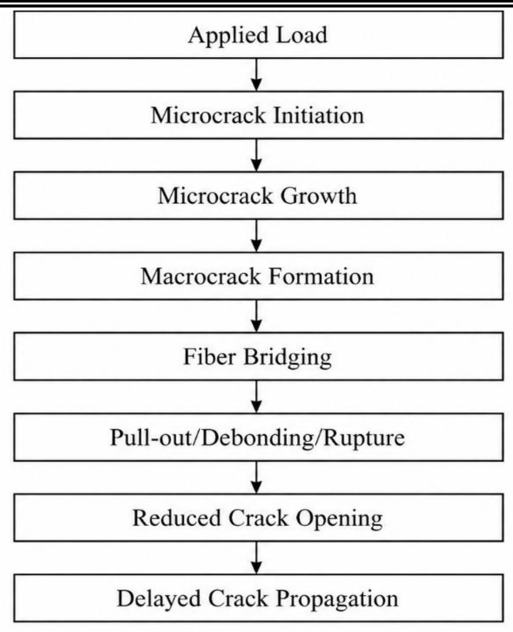

Figure 2: Schematic Mechanism of Crack Propagation and Fiber Bridging [8]

As can be seen in Figure 1 below, fiber bridging prevents further crack propagation and makes the failure mechanism less abrupt, becoming more energy absorbing.

4. INFLUENCE OF FIBER REINFORCEMENT ON CRACK CONTROL

Fiber reinforcing helps in controlling cracks through providing tension resistance in concrete. Fibers across a crack provide a bridge across the crack, transmit the tension force and prevent cracking of the concrete [9]. The efficiency of fiber reinforcing is based on several factors including the type of fiber, amount and orientation of the fibers, among others.

4.1 Steel Fibers

Steel fibers have excellent tensile properties and high stiffness, and are very useful in bridging macrocracks. Deformed fibers offer better mechanical interlocking and reduced pull-out resistance, leading to improved fracture toughness and energy absorption [10].

Figure 3: Steel Fibers [11]

4.2 Polypropylene Fibers

The function of polypropylene fibers is primarily for controlling micro-cracking and shrinkage-related cracking. The flexibility property of these fibers enables them to bridge small cracks and reduce crack width even though they contribute less to load-bearing capacity than steel fibers.

4.3 PVA Fibers

Bonding between the PVA fibers and the cementitious matrix is very high and it helps in forming several cracks. Therefore, PVA fibers are suitable in increasing ductility and reducing crack localization [12].

4.4 Basalt and Glass Fibers

Basalt fibers exhibit adequate tensile strength and help control the formation of micro-cracks, while at the same time providing durability. Glass fibers will assist in improving tensile strength and crack control; however, alkali resistant glass fibers are preferable.

4.5 Natural and Hybrid Fibers

Natural fibers like jute, sisal, and hemp may bridge cracks but present problems related to moisture uptake and durability. Fibers made up of different types are used in hybrid fiber systems to accomplish multi-scale crack bridging, where small fibers will control micro-cracks and large fibers will bridge macro-cracks.

4.6 Fiber Bridging and Failure Mechanisms

Fiber bridging is one of the most significant techniques of resisting cracks in composite materials. Fiber bridging involves fibers bearing tensile load through cracks. With an increase in crack length, the fibers might detach from the matrix or pull out, thus releasing energy. If the fiber is strong enough, fiber breakage might also take place [13].

4.7 Effect of Fiber Characteristics

The parameters such as dosage, length, aspect ratio, alignment, and distribution play an important role in controlling cracks. The increase in fiber dosage leads to the reduction in cracking tendency up to a limit, but higher fiber dosage can lead to poor workability. Longer and well-aligned fibers will be able to give better crack bridging effect.

Table 1: Influence of Fiber Characteristics on Crack Propagation in Concrete [14]

Fiber/Parameter	Influence on Crack Propagation
Steel fiber	Strong macrocrack bridging and improved fracture toughness
Polypropylene fiber	Controls microcracks and shrinkage cracks
PVA fiber	Promotes multiple fine cracks and improves ductility
Basalt fiber	Restricts microcrack development and improves crack resistance
Glass fiber	Improves tensile and crack-control behaviour
Natural fiber	Provides crack bridging with sustainability benefits
Hybrid fibres	Provides multi-scale micro- and macrocrack control
Fiber dosage	Controls the number of fibres available for crack bridging
Length and aspect ratio	Affect anchorage, pull-out and bridging efficiency
Orientation	Favor able orientation increases crack-bridging effectiveness
Distribution	Uniform distribution reduces localized crack development
Fiber–matrix bond	Controls stress transfer and energy dissipation

As can be seen from Table 1, various fibers have varying abilities for controlling cracks. Nevertheless, the overall effectiveness does not depend solely on the type of fiber but also on dosage, geometry, orientation, distribution, and fiber-matrix interaction [15].

5. EXPERIMENTAL AND NUMERICAL APPROACHES FOR CRACK ASSESSMENT

Various experimental and numerical methodologies are used for studying crack formation, growth, and fracture mechanics in fiber reinforced concrete. This includes details on the load-carrying capability, crack width, fracture energy, internal damage and matrix-fiber interactions. The various methodologies that are used in practice are detailed as follows [16].

5.1 Three-Point Bending and Direct Tensile Tests

Flexural tests based on three-point bending have become popular for assessment of the flexural strength, fracture energy, toughness, and behavior after cracking of fiber reinforced concrete. Notched specimens are subjected to loading up to failure so that the load-deflection and crack opening behavior could be analyzed. Tensile tests give the information about tensile strength, deformation ability, and crack bridging. Such testing is quite helpful in comparing the influence of various kinds of fibers and their quantities; however, tensile tests are more complex due to the need to control the stable cracking process and gripping of specimens.

5.2 Round-Panel Tests and Crack Mouth Opening Displacement (CMOD)

Round panels tests have been widely conducted in order to study the post-crack toughness and load carrying capacity of fiber reinforced concrete. The load is applied on the center of the panel, which causes cracking in the panel. The energy absorbing ability and remaining behavior of the specimen can be studied [17]. The Crack Mouth Opening Displacement (CMOD) is a crucial parameter employed in fracture tests for the measurement of crack mouth opening in a notched specimen. The load–CMOD relationship provides useful information about crack initiation, crack growth and the effectiveness of fibers in restricting crack opening.

5.3 Digital Image Correlation (DIC) and Acoustic Emission (AE)

Digital Image Correlation (DIC) is a non-destructive method that utilizes optics to detect deformation and crack formation while applying loads on the surface. It enables monitoring of full-field displacements and strains, and it aids in detecting the position of cracks and their development. Acoustic Emission (AE), on the other hand, senses stress waves formed through micro-cracks inside the material. Therefore, AE may give information regarding the damage evolution even before the formation of visible cracks.

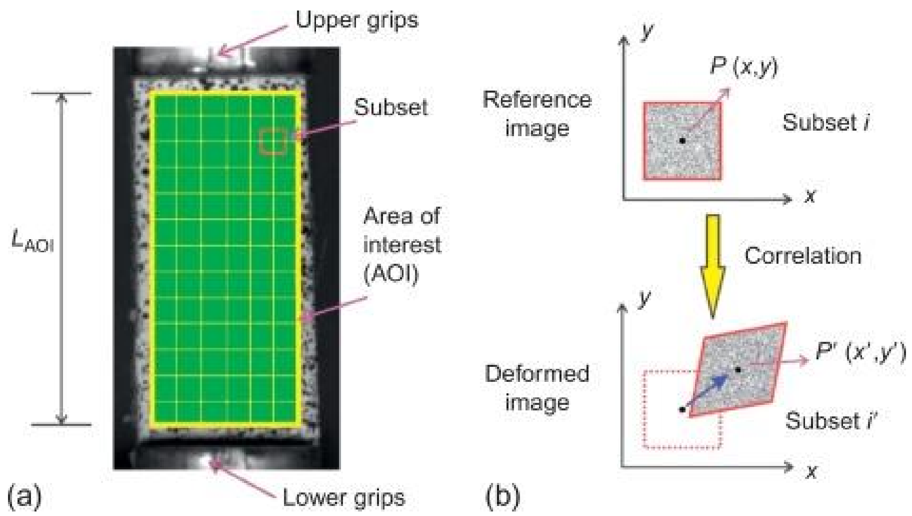

Figure 4: Digital Image Correlation (DIC) [18]

5.4 SEM and X-Ray Computed Tomography (CT)

The Scanning Electron Microscopy technique allows us to study the microstructure of concrete and the interface between fiber and matrix at magnifications. It helps to identify micro-cracks, fiber de-bonding, fiber pull out and interface damage, thus explaining the processes that contribute to the resistance of cracks. X-Ray Computed Tomography enables us to receive information about cracks, pores and fiber distribution in three dimensions without damaging the sample [19].

5.5 Fracture Mechanics and Numerical/Mesoscale Modelling

The fracture mechanics approach has provided the theoretical foundation for studying crack initiation and growth using parameters like the energy of fracture, fracture toughness, and crack opening behavior. In addition, numerical modeling and mesoscale modeling can be used by researchers to model the crack growth and failure mechanisms in fiber-reinforced concrete. With mesoscale modeling, the concrete matrix, aggregates, interfacial zones, and fibers can all be modeled, and the influence of fiber orientation on cracking mechanisms can be studied.

Table 2: Summary of Reviewed Studies on Fiber Reinforcement and Crack Propagation [20]

Reference	Focus of Study	Key Findings
Ghalehnovi et al. (2020) [21]	Crack width and propagation in recycled aggregate concrete beams with steel fibers	Steel fibers controlled crack development and reduced crack width.
Li et al. (2018) [22]	Effect of fiber type, volume fraction and aspect ratio on flexural and AE behaviour	Fiber characteristics significantly affected flexural response, damage development and crack resistance.
Wang et al. (2025) [23]	Effect of fiber type and content on mechanical properties and failure mechanisms	Fiber type and content influenced strength, deformation and failure behaviour; suitable fiber incorporation improved crack resistance.
Bayar & Bilir (2019) [24]	Machine-learning-based estimation of crack propagation in concrete	Machine learning showed potential for predicting crack propagation and supporting advanced fracture assessment.

6. APPLICATIONS, CHALLENGES AND FUTURE RESEARCH DIRECTIONS

The significance of using fiber reinforced concrete in contemporary construction has increased due to its capacity to prevent cracking, increase toughness and improve performance after cracking. Applications include both standard and advanced high-performance concrete structures. Nevertheless, issues like workability, distribution of fibers, orientation, durability and scale effects have to be considered properly for practical implementation [25].

- **Structural Applications:** Fiber-reinforced concrete is used in structural elements where better crack control, toughness and post-cracking properties are required. The use of fiber can help in minimizing the crack width and also enhance the load carrying capacity of the concrete even if the matrix has been cracked.
- **Pavements and Industrial Floors:** FRC is very popular in concrete pavements, industrial floors and slabs as the addition of fibers prevents shrinkage and service cracks, improves impact resistance and increases fatigue strength [26]. The usage of steel and synthetic fibers may additionally help in stress distribution and minimizing formation of local cracks.
- **Tunnel Linings and Shotcrete:** The addition of fibers in shotcrete makes it more effective in the construction of tunnels and other underground structures. Fibers offer reinforced distribution throughout the sprayed concrete structure and increase its durability, crack resistance and ability to absorb energy. Steel and synthetic fibers are especially effective in such applications [27].
- **Precast Concrete:** FRC is effective in precast elements due to relatively consistent distribution of fibers which can be achieved under controlled conditions during manufacturing.
- **Repair and Rehabilitation:** These materials have been increasingly adopted as solutions for the rehabilitation and strengthening of concrete structures [28]. The crack bridging property and good post-cracking behavior may be effective in controlling cracking in repaired zones and increase the durability of deteriorated structures.
- **UHPC/UHPFRC:** Ultra high-performance fiber reinforced concrete (UHPFRC) is a fiber-reinforced concrete made of a dense and high-strength cementitious matrix that is capable of high strength, ductility and crack resistance [29]. This material is especially suited for bridges, precast products, strengthening and exposed structural elements.
- **Fiber Orientation, Scaling Effects and Durability:** The fiber orientation plays a crucial role in influencing crack resistance as the fibers that cross the crack line offer higher crack resistance than the ones parallel to the crack line. Furthermore, the laboratory scale testing of such materials cannot be directly transferred to the real scale structural elements due to the difference in casting and structural geometry [30].

7. CONCLUSION

The literature review clearly shows that fiber reinforcement is an efficient method for the control of crack initiation, propagation and post-crack behaviour in concrete. The fiber reinforcements that include steel fibers, polypropylene, PVA, basalt fibers, glass, natural and hybrid fibers can bridge the emerging cracks, absorb tensile stresses and dissipate fracture energy due to their debonding, pull-out and fiber rupture processes. However, the efficiency of fiber reinforcement highly depends on the type, amount, length, aspect ratio, orientation, dispersion and interaction between fiber and matrix. Experimental methods including bending test, tensile test, CMOD, DIC, acoustic emission, SEM and X-ray CT and fracture mechanics and numerical simulation can be very useful to get valuable data about crack behavior on different scales. Therefore, fiber-reinforced concrete can have a significant role in structural members, pavements, tunnel lining, pre-cast products, repairing jobs and UHPC/UHPFRC. Yet, workability, dispersion, orientation, scale effect and durability problems can exist. Consequently, the future research on this topic should be aimed at optimizing fiber mixtures, advanced crack monitoring methods, structural scale validation, numerical modeling and sustainable fiber systems.

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