MITIGATING FLEXURAL CRACKS IN CONCRETE BEAMS USING DIVERSE FIBERS: A REVIEW

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Abstract- Flexural cracking remains a critical challenge in reinforced concrete beams, adversely affecting structural durability and service life. This review investigates the potential of incorporating cotton, glass, and human hair fibers to enhance the flexural performance of concrete. Emphasizing both mechanical behavior and environmental sustainability, the study draws upon 32 peer-reviewed sources published between 2010 and 2025. The selected fibers are evaluated based on tensile properties, crack mitigation capabilities, and applicability in sustainable construction. Comparative analysis reveals that while glass fibers offer superior strength, cotton and human hair fibers present notable benefits in terms of biodegradability and cost-effectiveness. A synthesis of secondary data provides theoretical insight into the fibers' efficacy in resisting flexural stress. The findings support fiber reinforcement as a viable strategy for improving concrete performance while aligning with global sustainability goals.

Keywords- Cotton Fiber, Flexural Cracks, Fiber Reinforced Concrete, Glass Fiber, Human Hair Fiber

1. Introduction

Concrete remains a cornerstone material in modern construction, prized for its high compressive strength, longevity, and accessibility. Nonetheless, its primary limitation is its inadequate tensile strength, making it vulnerable to flexural cracks when subjected to bending stresses [1]. These cracks often initiate in the tension zone of beams and spread upward as the tensile stress surpasses the material's threshold. Over time, such fissures compromise both aesthetics and durability by facilitating the entry of moisture and chlorides, which in turn hasten steel reinforcement corrosion [2]. This degradation can threaten the structural safety and shorten the service life of concrete members. While conventional reinforcement techniques offer partial relief, they may not fully eliminate cracking or might be financially unfeasible for certain projects. As a result, researchers are increasingly turning toward fiber-reinforced concrete as an economical and effective alternative. When fibers are uniformly distributed in the matrix, they help bridge microcracks, enhance tensile strength, and improve ductility and stress redistribution [3] This innovation aligns with the growing demand for durable and sustainable infrastructure solutions.

Recent advancements in fiber-reinforced concrete have introduced several unconventional fibers such as cotton, glass, and waste human hair. Cotton fibers are natural and biodegradable, contributing to post-crack toughness and reducing shrinkage cracks, thereby promoting eco-friendly construction practices [4][5]. Glass fibers, while offering exceptional tensile strength and stiffness, pose challenges due to their high energy manufacturing process and non-biodegradable nature [6][7]. On the other hand, human hair fibers an abundant and renewable keratin-based waste product present a unique opportunity for recycling while providing elasticity and tensile benefits [8][9]. These fiber types differ not only in mechanical behavior but also in terms of cost, availability, and environmental impact. Evaluating these differences is vital to identifying their practicality for real-world applications. Moreover, their inclusion in concrete supports global sustainability targets by reducing material waste and promoting circular resource use, especially in resource-constrained regions.

This paper explores the comparative potential of cotton, glass, and waste human hair fibers in minimizing flexural cracking in concrete beams. The inclusion criteria focused on studies that investigated mechanical properties, particularly flexural strength, and the role of fiber reinforcement in crack control and sustainability. Research that concentrated solely on compressive or non-structural applications was excluded unless it offered substantial insight into fiber performance under flexural stress. By examining 32 carefully selected peer-reviewed publications from 2010 to 2025, retrieved through targeted searches on ScienceDirect, and Google Scholar, the study offers a thematic synthesis of existing findings. The uniqueness of this review lies in its focused comparison of three fiber types with varying mechanical and environmental characteristics, highlighting the often-overlooked use of human hair as a sustainable construction material. The objective is to inform future research and practical applications by drawing insights from current literature rather than original experimentation.

2. Flexural Cracks in Concrete Beams

Flexural cracks are among the most frequently observed forms of distress in reinforced concrete beams, emerging primarily due to bending-induced tensile stresses in the lower regions of the cross-section. Since concrete is inherently weak in tension, these stresses lead to the development of vertical cracks on the tension face when the applied moment exceeds the section's cracking moment. Such cracking not only affects the structural aesthetics but also serves as a critical point of ingress for moisture and aggressive agents, accelerating the deterioration of embedded reinforcement [2]. As corrosion initiates and progresses, the bond between concrete and steel weakens, potentially compromising load-bearing strength and leading to premature failure. The formation and propagation of flexural cracks are thus important indicators of serviceability concerns in structural elements. Effective crack control is essential to maintaining the durability, integrity, and performance of concrete structures under long-term loading and environmental exposure. Hence, it becomes imperative to explore materials and design strategies that limit crack development at both early and later stages of structural use.

One promising approach for mitigating flexural cracking is the incorporation of discrete fibers into the concrete matrix. Fiber-reinforced concrete (FRC) has been demonstrated to improve tensile behavior, increase post-cracking toughness, and reduce crack width by facilitating stress redistribution across microcracks [1]. Depending on the fiber type such as glass, cotton, or human hair concrete can achieve different mechanical and environmental performance enhancements. Glass fibers, due to their high tensile strength and stiffness, provide effective crack bridging and resistance, while natural fibers like cotton and human hair offer the added benefits of biodegradability and waste utilization [10]. The integration of such fibers contributes not only to crack control but also to promoting sustainable construction practices. Research has shown that even small volumes of fiber can significantly improve flexural strength and delay the formation of critical cracks in beam elements. As a result, fiber reinforcement stands as a practical and eco-efficient method to enhance the service life and reliability of reinforced concrete beams. Figure 1 (a) depicts different types of cracks in RC beams [11]. Figure 1 (b) shows cracks in concrete beams observed at the Author's place of work.

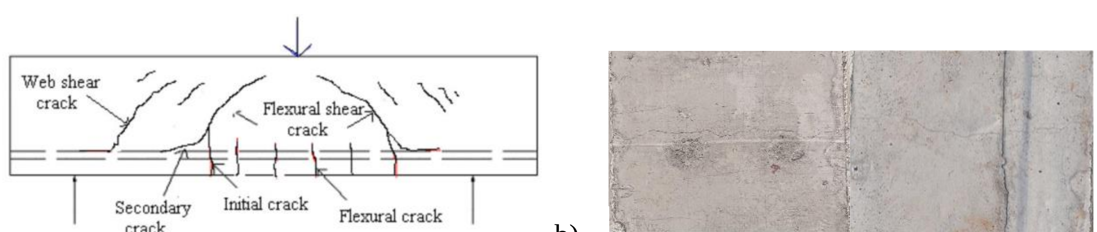
a)  b)

Figure 1 Flexural Cracks in Concrete Beams, a. Types of Cracks in Beams, and b. Flexural Cracks in Beams

3. Governing Factors of Flexural Cracking

Flexural cracking in concrete beams is influenced by a convergence of material, structural and environmental factors. Concrete's relatively low tensile strength makes it prone to cracking when bending stresses exceed its inherent strength

[12]. External loads especially those that are excessive, dynamic or cyclic further increase tensile strain and accelerate crack propagation. Internal stress development due to drying, autogenous, or temperature-induced shrinkage also plays a critical role, as these movements in restrained conditions generate tensile force that initiates cracking. Reinforcement detailing, including bar spacing and bonding, directly controls crack width and distribution; insufficient reinforcement often results in wider, poorly distributed cracks [12]. Lastly, deficiencies in mix design, such as improper water to cement ratio, inadequate compaction, and poor curing, degrade concrete integrity and heighten crack susceptibility [13]. A comprehensive approach addressing all these elements during design and construction is essential to mitigate flexural cracking and enhance structural durability. These interrelated parameters are outlined in Table 1, which summarizes the influence on flexural cracking.

Table 1 presents a systematic overview of the principal factors affecting flexural cracking in concrete beams. The material-related limitations, such as low tensile strength, form the fundamental basis for crack formation. Structural factors, especially high-amplitude or variable loading conditions, contribute significantly to stress fluctuations that exacerbate cracking tendencies [14]. Environmental influences, such as shrinkage and thermal changes, are especially critical in restrained conditions where movement is restricted, resulting in internal tensile stress development [15]. The configuration and effectiveness of reinforcement influence both crack control and structural serviceability, with poorly designed systems allowing more pronounced crack widths [12]. Lastly, construction quality including mix proportioning and workmanship directly impacts the durability and integrity of concrete. Inadequate practices elevate the likelihood of premature cracking due to reduced cohesion and poor hydration [13]. Together, these factors underscore the need for a holistic approach during design and execution to limit flexural crack development.

Table 1 Primary Factors Influencing Flexural Cracking

Governing Factor	**Influence on Flexural Cracking**
Low Tensile Strength	Cracks initiate when bending stresses exceed tensile strength.
Load Characteristics	High-magnitude, cyclic, or dynamic loads exacerbate tensile stress and crack growth.
Shrinkage & Temperature	Drying, autogenous, and thermal stresses in restrained concrete generate tensile forces.
Reinforcement Configuration	Poor reinforcement design leads to wider cracks due to insufficient stress distribution.
Mix Quality & Workmanship	Inadequate mix proportions, compaction, or curing weaken concrete and elevate cracking risk.

4. Performance and Sustainability of Fiber-Reinforced Concrete

Incorporating fibers such as cotton, glass, and human hair into concrete has shown considerable potential in enhancing mechanical performance and promoting sustainable construction. As illustrated in Figure 2, the selection of fiber type plays a crucial role in determining the overall behavior of the composite. Cotton fibers, being biodegradable and renewable, significantly improve ductility and crack resistance; however, their moisture absorption can adversely affect workability. Glass fibers contribute exceptional tensile strength and crack control, making them suitable for high-performance structural applications, though their non-biodegradable nature presents environmental concerns. Human hair fibers, a cost-effective and eco-friendly alternative, enhance tensile strength and ductility, with optimal performance typically observed at 1.5% by weight of cement. Each fiber type exhibits distinct mechanical and environmental characteristics, necessitating thoughtful selection aligned with project-specific performance and sustainability goals.

P

a) b) c)

Figure 2 Fiber Reinforced Concrete, a. Cotton Fiber Concrete [16], b. Glass Fiber Concrete [17], and c. Waste Human Hair [18]

A comparative analysis presented in Table 2 highlights the mechanical and environmental attributes of the selected fibers. Glass fibers exhibit superior tensile strength and stiffness, making them ideal for structural enhancement, but their energy-intensive production and lack of biodegradability limit their sustainability [19][20][21]. In contrast, cotton and human hair fibers, while offering comparatively lower mechanical strength, demonstrate enhanced ductility and crack resistance, coupled with environmental benefits such as biodegradability and reuse of waste materials. Table 3 outlines additional practical considerations: cotton fibers promote green construction but may compromise workability due to moisture sensitivity; glass fibers ensure high structural reliability but entail environmental costs; and human hair fibers provide an economical and sustainable solution, though they present challenges related to uniform dispersion and fiber-matrix bonding. [19][20][21][22].

Table 2 Mechanical & Environmental Performance at Typical Fiber Content

Fiber Type	Tensile Strength (MPa)	Modulus (MPa)	Flexural/Crack Resistance	Sustainability	Typical Issues
Cotton	287–597 MPa	5000-12,000 MPa	Good	Biodegradable, renewable	Clumping; moisture uptake
Glass	1,000–3,500 MPa	70,000-85,000 MPa	Excellent	Non-biodegradable	Brittleness; mixing challenges
Human Hair	200–380 MPa	4000-5000 MPa	Very good	Biodegradable; waste-reuse	Variable quality; adhesion issues

Table 3 Pros, Cons, and Application Barriers

Fiber Type	Strengths	Limitations	Key Application Notes
Cotton	Enhances ductility; eco-friendly	Lower strength than glass; absorbs moisture	Suited for shrinkage control; sustainable or green projects
Glass	Very high strength; superior flexural behavior	Energy-intensive; risk of microcracking at high dosage	Ideal for structural-grade and high-performance concrete
Human Hair	Cost-effective; promotes waste minimization	Adhesion variability; yield inconsistency	Suitable for pilot-scale or low-cost sustainable construction

Table 4 illustrates the measurable impact of incorporating cotton, glass, and human hair fibers on the flexural strength of concrete beams. Glass fibers consistently provide the highest improvement in flexural performance, with strength gains ranging from 20% to 45%, owing to their high tensile strength and stiffness. Human hair fibers, while offering moderate improvements between 12% and 25%, present a sustainable and cost-effective alternative, especially suitable for low-cost applications. Cotton fibers demonstrate modest strength enhancements (10–18%) but significantly contribute to post-crack toughness and environmental sustainability. Overall, the results support the feasibility of using natural and waste fibers for improving the structural performance of concrete, particularly when optimized for dosage and fiber compatibility.

Table 4 Effect of Fiber on Flexural Strength of Concrete Beams

Fiber Type	Reference Study	Dosage (% by cement wt.)	Increase in Flexural Strength (%)	Remarks
Cotton	Ghulam et al. (2020) [5]	1.0–2.0%	10–18%	Improved post-crack behavior; prone to moisture sensitivity
Glass	Maranan et al. (2015) [8]	0.5–1.5%	20–45%	High stiffness; superior crack resistance
Human Hair	Ahmed and Al Numan (2022) [2]	1.0–2.0%	12–25%	Effective at low cost; variation in bonding noted

5. Conclusion

This paper explores the potential application of fiber reinforcement in concrete beams through a vigorous research exploration from highly reputed journals. The current effort is to compose all published information related to the subject. Following conclusions can be drawn from the conducted study:

- Flexural cracking in concrete structures is a persistent challenge, and fiber reinforcement offers an effective approach to enhance tensile strength and control crack propagation.
- Cotton, glass, and human hair fibers demonstrate distinct performance characteristics as glass improves mechanical strength, cotton contributes to sustainable construction, and human hair provides a novel use of waste with notable improvements in toughness.
- Utilizing natural and waste-based fibers promote environmentally conscious construction practices and aligns with principles of circular economy in civil engineering.

This study highlights the potential of cotton, glass, and human hair fibers in enhancing concrete flexural performance and promoting sustainability. However, further research is required to optimize fiber content, assess long-term durability, and develop standardized guidelines. These steps are vital for practical adoption in structural engineering.

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