ENHANCING CONCRETE SUSTAINABILITY: NATURAL FIBRE REINFORCEMENT FOR SHRINKAGE CRACK MITIGATION IN CONCRETE STRUCTURES

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Abstract- Shrinkage cracking is one of the most common flaws encountered in reinforced cement concrete (RCC) structures, primarily due to volumetric changes caused by moisture loss and improper curing. These cracks can significantly compromise the durability, aesthetics, and serviceability of concrete elements. This review explores the application of natural fibre reinforcement as a sustainable and effective solution to mitigate shrinkage cracks in concrete structures. Unlike synthetic fibres, natural fibres are biodegradable, cost-effective, and environmentally friendly aligning with global sustainability goals. A detailed review of crack types, fibre characteristics, governing parameters for shrinkage, and fibre volume dosage considerations was conducted using recent literature and the results are thoroughly reported. Key standards such as ACI 544.3R-08, ASTM C1116, and EFNARC guidelines were referenced to establish acceptable fibre content and performance benchmarks. Findings show that natural fibres like jute, sisal, and coconut, at optimized volume fractions, enhance crack resistance, increase flexural strength by up to 89%, reduce water absorption by approximately 25%, and improve concrete's post-crack behavior and mechanical properties. This review aims and supports the use of natural fibres in concrete not only as a technically sound method for crack control but also as a step forward in achieving sustainable and resilient construction practices.

Keywords- Fibre Volume Fraction, Fibre-Reinforced Concrete (FRC), Shrinkage Cracks, Sustainable Construction

1 Introduction

Concrete stands as a cornerstone in modern construction due to its versatility, strength, and durability. However, its inherent brittleness and susceptibility to cracking pose significant challenges to structural integrity and longevity. Among the various types of cracks, shrinkage cracks are particularly prevalent, arising from volumetric changes as concrete cures and dries. Addressing these issues is crucial for enhancing the performance and sustainability of concrete structures. Incorporating fibres into concrete mixes has emerged as a promising solution, offering improved tensile strength, crack resistance, and overall durability. Utilizing natural fibres not only leverages renewable resources but also contributes to cost reduction and environmental sustainability, aligning with the growing emphasis on green construction practices.

Cracks in concrete are categorized based on their causes and characteristics. Common types include plastic shrinkage cracks, which occur shortly after pouring due to rapid moisture loss; drying shrinkage cracks, resulting from long-term moisture evaporation; and thermal cracks, caused by temperature variations leading to expansion and contraction [1]. Structural cracks, such as flexural and settlement cracks, arise from external loads or foundation movements. These cracks compromise the structural integrity and aesthetic appeal of concrete structures, necessitating effective mitigation strategies

[2]. Research has explored the integration of various fibres into concrete to enhance its properties and mitigate cracking. Natural fibres, including coconut, sisal, and jute, have been studied for their effectiveness in controlling shrinkage cracks. For instance, incorporating 1% volume of sisal fibre into concrete significantly increased the energy required to initiate cracks, demonstrating enhanced toughness [3]. Similarly, coconut fibres have been shown to improve crack resistance and maintain strength even at elevated temperatures. These findings highlight the potential of natural fibres as sustainable alternatives to synthetic fibres in concrete mixes [4].

Recent studies have demonstrated that the incorporation of natural fibres into concrete can significantly enhance its mechanical properties [5]. For example, the addition of jute fibres has been shown to improve the flexural strength and toughness of concrete, making it more resistant to cracking under load [6]. Similarly, the use of kenaf fibres has been associated with increased tensile strength and reduced shrinkage in concrete mixes. Likewise, Qamar, et al.[7] states that plaster having natural fibres improves the lateral resistance of mortar-free interlocking walls. These improvements are attributed to the fibres' ability to bridge microcracks and distribute stress more evenly throughout the concrete matrix [8]. Despite the promising results, challenges remain in standardizing the use of natural fibres in concrete. Variations in fibre properties, such as length, diameter, and composition, can affect the consistency and performance of fibre-reinforced concrete [9]. Moreover, the lack of comprehensive guidelines for fibre volume and dosage complicates the optimization of mix designs [10]. Addressing these gaps is essential for the broader adoption of natural fibre-reinforced concrete in structural applications.

This review aims to investigate the role of natural fibre reinforcement in mitigating shrinkage cracks in concrete structures. By analyzing the types and causes of cracks, evaluating the effectiveness of various natural fibres, and exploring optimal fibre volumes and dosages, the research seeks to develop sustainable and cost-effective solutions for enhancing concrete durability. The findings are expected to contribute to the advancement of green construction practices and the development of standardized guidelines for natural fibre-reinforced concrete.

2 Identification of Shrinkage Cracks in RCC Buildings

The identification and assessment of shrinkage cracks involve a combination of visual inspections and standardized testing methods [11]. Shrinkage cracks in reinforced cement concrete (RCC) structures as shown in figure 1 primarily result from volumetric changes due to moisture loss and temperature variations. These cracks can be categorized into plastic shrinkage cracks, occurring shortly after concrete placement, and drying shrinkage cracks, which develop over time as the concrete loses moisture [12]. As illustrated in figure 1, plastic shrinkage cracks typically manifest within the first few hours after placement, primarily due to rapid moisture loss from the surface, leading to tensile stresses that exceed the concrete's early-age strength [3, 13]. Drying shrinkage cracks develop over a longer period as the concrete loses moisture to the environment, resulting in volumetric contraction [14]. Thermal cracks arise from temperature gradients within the concrete mass, causing differential expansion and contraction. Structural cracks, such as flexural and settlement cracks, are induced by external loads or foundation movements, compromising the structural integrity of the concrete element [15]. Understanding these crack types and their underlying causes is crucial for implementing effective mitigation strategies.

(a) Early Shrinkage Cracking (b) Plastic Shrinkage Cracking (c) Drying Shrinkage Cracking

Figure 1: Shrinkage crack propagation (a) happens within the first day or two after placing concrete (b) Within the first few hours after placing the concrete (c) Days to weeks after setting, as concrete begins to dry and harden [16]

Visual inspections focus on detecting surface cracks, noting their width, length, and pattern, which can provide insights into their origin. For a more detailed analysis, non-destructive testing methods such as ultrasonic pulse velocity and infrared thermography can be employed to assess the depth and severity of cracks [17]. Standards like ACI 224.1R-07 provide guidelines for evaluating and repairing cracks in concrete structures, emphasizing the importance of understanding the cause before selecting a repair method. Additionally, ASTM C1581/C1581M-18a outlines procedures for determining the age at cracking and induced tensile stress characteristics of mortar and concrete under restrained shrinkage, offering a standardized approach to assess shrinkage cracking. Adhering to these standards ensures a systematic and effective approach to managing shrinkage cracks in RCC structures.

3 Causes and Remedial Measures for Shrinkage Cracking in Concrete

Shrinkage-induced cracking in reinforced cement concrete (RCC) elements arises from a combination of intrinsic material properties and external environmental factors. Key parameters influencing shrinkage include the water-cement ratio, aggregate characteristics, cement content, ambient temperature, humidity, and curing practices. High water-cement ratios lead to increased drying shrinkage, while aggregates with high shrinkage potential exacerbate the issue [18]. Environmental conditions such as elevated temperatures and low humidity accelerate moisture loss, intensifying shrinkage stresses [14]. Inadequate curing further enhances these effects by allowing rapid evaporation of water from the concrete surface, leading to early-age cracking [19]. These factors collectively contribute to the development of shrinkage cracks, compromising the durability and serviceability of RCC structures. Figure 2 summarizes the primary causes of shrinkage cracking, their estimated contribution percentages, and the relevant standards or authors referencing these factors:

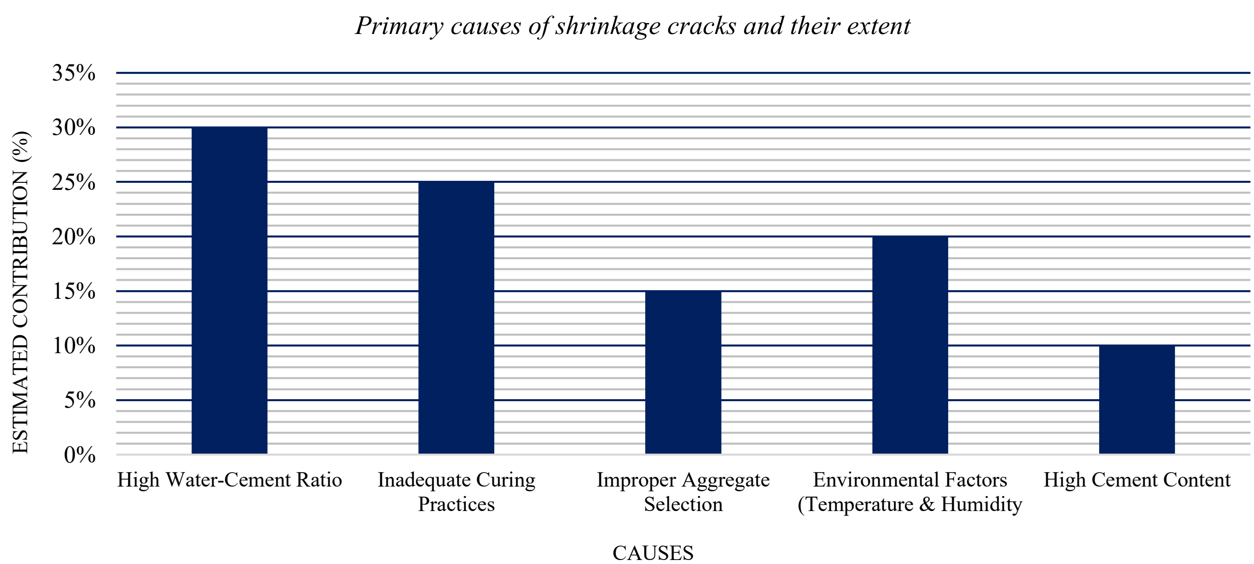

Figure 2: Primary causes of shrinkage cracking as per ACI224R-01 and ACI224.1R-07 [19]

Mere plain concrete (PC) is particularly susceptible to shrinkage cracking due to its limited tensile strength and inability to distribute stresses effectively. Thus, this study proposes a solution which is natural fibre (as shown in fig. 03) additives in concrete that can play a vital role in mitigating shrinkage and related cracking compared to plain concrete (PC). Shrinkage, especially at early ages due to rapid moisture loss, often leads to plastic and drying shrinkage cracks in plain concrete. When natural fibres as illustrated in fig. 3 such as jute, coir, sisal, or hemp are incorporated into the concrete mix, they help bridge micro-cracks and distribute internal stresses more uniformly, effectively delaying crack formation and reducing crack width. However, even in reinforced concrete, which mainly controls structural cracks, natural fibres help mitigate non-structural shrinkage cracks by enhancing the tensile strain capacity and providing early-age crack resistance [3, 20]. Therefore, understanding the governing parameters and implementing appropriate design and construction practices are essential for mitigating shrinkage cracking in RCC members.

Figure 3: Various fibre additives used in concrete, including natural, synthetic, and steel fibres [16]

Hence understanding the governing parameters and the respective solutions is crucial for the effective design and construction of RCC structures. By addressing these factors through appropriate material selection, mix design, and construction practices, the incidence of shrinkage cracking can be significantly reduced, leading to more durable and serviceable concrete structures.

4 Optimizing Fibre Volume and Dosage for Shrinkage Crack Control

Incorporating fibres into concrete mixes necessitates meticulous attention to fibre volume fractions and dosage to achieve desired mechanical properties and durability. The fibre volume fraction (FVF) refers to the percentage of fibre volume relative to the total volume of the composite, while dosage typically denotes the weight of fibres added per unit volume of concrete, expressed in kg/m³ or lb/yd³. Proper selection of FVF and dosage is crucial, as insufficient fibre content may not provide the intended reinforcement benefits, whereas excessive fibre content can lead to issues such as reduced workability and fibre clumping. Table 1 highlights some studies which demonstrated that optimal fibre content varies depending on the type of fibre and the specific performance requirements of the concrete. Najaf, et al. [21] showed that 1.5% polypropylene fibres greatly enhance ductility and impact resistance. This aligns with Khan, et al. [22], who observed similar improvements using glass fibres, though only up to an optimal 1% dosage. Both support the notion of an optimal range beyond which workability may be compromised. The following table 1 summarizes typical fibre volume fractions and the respective effects on concrete.

Table 1 Effects of Fibre Volume Fraction on Concrete Properties via scholarly aspect [16]

Fibre Type	Volume Fraction (%)	Observed Effects on Concrete Properties	Reference(s)
Polypropylene Fibres	1.5	Compressive strength increased by up to 36% Flexural strength increased by up to 89% Enhanced ductility and impact resistance	Najaf, et al. [21]
Glass Fibres	1	Compressive strength increased by 15.38% Split tensile strength increased by 58.94% Flexural strength increased by 17.54% Strength decreased beyond 1% dosage	Khan, et al. [22]
Hybrid Fibres (Steel + Polyester	0.2 + 0.3	Improved toughness and durability Split tension capacity enhanced by 72% Reduced water absorption by 25%	Christopher, et al. [23]

Table 2 highlights some standards and guidelines that provide recommendations for fibre content in concrete mixes to ensure consistency and performance. According to ASTM C1116/C1116M, synthetic microfibres are typically used at dosages ranging from 0.3 to 0.9 kg/m³ (0.03% to 0.1% by volume) for controlling plastic shrinkage cracking. For macro-synthetic fibres, dosages can range from 1.8 to 12 kg/m³, depending on the desired performance characteristics. Steel fibres are often incorporated at volume fractions between 0.5% and 2.0%, with dosages adjusted based on the specific application and performance requirements. The American Concrete Institute's ACI 544.3R-08 guide emphasizes the importance of selecting appropriate fibre types and dosages to achieve the desired balance between workability and mechanical performance. Table 2 summarizes typical fibre volume fractions and dosages for various fibre types as recommended by relevant standards and studies

Table 2 Recommended Fibre Volume Fractions and Dosages [24]

Fibre Type	**Volume Fraction (%)**	**Dosage (kg/m³)**	**Reference**
Polypropylene (Micro)	0.03 – 0.1	0.3 – 0.9	ASTM C1116/C1116M
Polypropylene (Macro)	0.1 – 0.3	1.8 – 12	ASTM C1116
Steel Fibres	0.25 – 2.0	20 – 60	ACI 544.3R-08
Glass Fibres	0.01 – 0.03	0.29 – 0.88	ACI 544.3R-08

5 Conclusion

The incorporation of natural fibres in concrete mixes presents a promising and sustainable solution to mitigate shrinkage cracking in RCC structures. By enhancing tensile strength, controlling microcrack development, and improving overall durability, fibre-reinforced concrete significantly extends the service life of structural elements while reducing maintenance needs. This approach aligns directly with several United Nations Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production) by promoting eco-friendly construction practices, reducing reliance on synthetic materials, and encouraging the use of agricultural waste. The key findings of this review are:

1 Shrinkage cracks in RCC are primarily caused by volumetric changes due to drying, poor curing, high water-cement ratios, and environmental exposure.
2 Natural fibres such as jute, sisal, and coconut improve concrete's crack resistance, as evidenced by up to 89% improvement in flexural strength and up to 72% enhancement in split tension capacity.
3 Fibre volume fraction and dosage significantly influence concrete's mechanical performance, durability, and crack resistance.
4 Recent research (2023–2025) supports the optimal use of fibres in the range of 0.3% to 2.0% by volume, depending on the fibre type and application.
5 Relevant standards such as ACI 544.3R-08, ASTM C1116, and EFNARC guidelines help guide proper fibre selection and dosage control.
6 Overall, natural fibre-reinforced concrete not only improves structural performance but also supports sustainable, low-carbon construction practices aligned with global development goals.

In summary, fibre-reinforced concrete using natural fibres offers a durable, eco-friendly, and cost-effective solution for crack mitigation in RCC buildings. These findings are backed by recent experimental data and benchmark standards (ASTM C1116, ACI 544.3R-08), which validate fibre dosages and performance expectations for shrinkage crack control. This approach supports the construction industry's transition toward more sustainable and resilient practices.

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