FIBER-REINFORCED CONCRETE FOR CRACK RESISTANCE: A REVIEW STUDY

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Abstract- Concrete is widely recognized for its high compressive strength when compared with other construction materials. Nevertheless, it has critical flaws, as low tensile strength, brittleness and vulnerability to crack propagation. Plastic shrinkage and thermal cracking are two of the most critical early age cracking problems in concrete structures in hot climates. Plastic shrinkage cracking occurs when surface moisture loss from high temperature, low humidity and wind occurs rapidly before the concrete sets. Whereas, thermal cracking results from internal temperature gradients that are established during cement hydration and the thermal expansion behavior of aggregates. Focusing on the effectiveness of both plastic shrinkage and thermal cracking, two commonly occurring types of cracking, this study investigates the potential of various fiber types including steel, polypropylene, glass, basalt, carbon, and natural plant fibers. Among these, steel fibers are noticeably superior than the others, in resisting both forms of cracking because of their high tensile strength, crack bridging, and thermal stability. The research concludes that use of steel fibers in concrete mix designs can greatly enhance the structural integrity and service life of concrete subjected to extreme environmental exposure.

Keywords- Compressive Strength, Brittleness, Plastic Shrinkage, Thermal Cracking, Steel Fiber

1 Introduction

The high compressive strength of concrete makes it one of the most widely used construction materials, being also environmentally suited. Drawbacks are brittleness, low resistance to crack propagation, poor tensile strength. [1] [2]. The composition of concrete includes aggregates and sometimes admixtures. As the paste hardens due to the chemical reaction of the cement with water, the aggregates are bound together by the paste, which is made of cement and water, to make a rock like mass [3]. With its high compressive strength it is however brittle, thereby being less able to resist tensile stress or deformations. Concrete, particularly at low strains is extremely brittle, and owing to the low strain capacity of the material in tension, it has low toughness. Addition of randomly distributed fibers to concrete has attracted a lot of research that tries to improve its toughness. As a result, it has been embraced all over as a way of enhancing the energy dissipation, toughness and crack propagation control or arrest of concrete. [4] [5] [6]. The technique has been utilized in ancient times, to reinforce brittle matrix materials. Cracking is controlled by randomly distributed fibers which inhibit crack growth by arresting the formation of cracks and by preventing the growth of the existing cracks [7].

Fibers are used to strengthen or reinforce concrete by limiting the unstable crack propagations both on a microscopic level and macroscopic level due to their random orientation. [8] [9]. FRC is characterized by a stiffness degradation (so-called strain-softening) even when macro-cracks exist and it has been shown to have the potential to control cracks efficiently [10] [11]. Potential formation of macrocracks could result in corrosion of the steel reinforcement and thus imperative to reducing crack width through fibers addition for enhancing durability of RC structural members [12]. The infusion of fibers in concrete significantly improves its toughness, strength, crack resistance and tensile capabilities. The fibers limit the crack propagation at both micro and macro level and hence improve the durability and structural integrity [13] [14]. It is especially important in reducing macrocrack development, which may result in steel reinforcement corrosion in reinforced concrete.

Fiber reinforced concrete (FRC), where there is haphazard distribution of artificial fibers, is reported to minimize plastic shrinkage cracks, and improve impact resistance and toughness compared to plain concrete. [15]. Synthetic fibers, like most fibers utilized in concrete, increase the post-cracking behavior, especially increasing ductility in the tensile response. [16]. FRC arrests opening and widening of micro cracks, thus enhancing deformation ability under tension and compression. However, synthetic fibers do not perform well in terms of stress transfer due to their lower elastic modulus than steel fibers, and hence, the functionality of synthetic fibers in post-cracking tensile response in fiber-reinforced concrete (FRC) is observed to be less significant. Besides this, synthetic fibers yield a favorable influence upon ultimate splitting tensile strength and flexural strength in splitting and bending tests, when compared to the corresponding direct tensile tests, despite the fact they do give a slight lift in tensile strength. [17].

Concrete possesses a very high compressive strength, exhibits low tensile capacity and brittleness that restrict it from performance. Adding fibers to concrete makes it tough, crack resistant, and longer life, bridging and arresting cracks at microscopic and macro levels. Especially if synthetic or steel fibers are added, fiber reinforced concrete (FRC) has exhibited better performance in tension and flexure, and reduced shrinkage and improved crack control [14]. In this manner, the addition of fiber is a practical and effective option to improve the mechanical behavior and service life of concrete structures.

2 Flaws in Concrete Structure

A building structure constructed in a hot climate may experiences two type of cracks which are discussed below:

2.1 Plastic Shrinkage Cracks

Horizontal concrete surfaces under extreme climatic conditions (typically high temp, low RH, wind) that may lead to rapid evaporation, plastic shrinkage cracks will happen before the concrete setting. [18]. Evaporation of water that forms menisci and high tensile stresses in the capillary water at the surface is the main driving force for plastic shrinkage cracking [19]. After bleeding water on the concrete surface is consumed by evaporation, water menisci are formed. Capillary stresses produced by these menisci compress the whole concrete and causes it to shrink [20]. Theoretically, when the concrete surface is not dried, plastic shrinkage cracks will not take place as there will be no development of negative capillary pressure [21]. Boshoff [22] suggested a simplified basis to approximate the severity of plastic shrinkage cracking expressed in terms of the evaporation rate, bleeding rate and initial setting time, and proved that the criterion of severity and area of plastic shrinkage cracking on the concrete surface had close correlation. The Plastic Shrinkage Cracking in a concrete structure is shown in Figure 1.

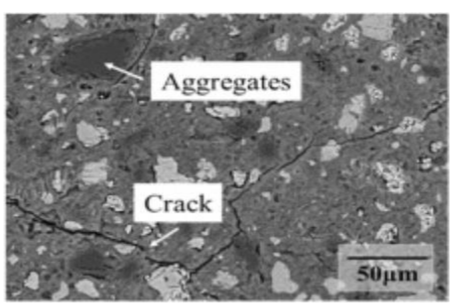

Figure 1 *Plastic Shrinkage Cracking [23]*

2.2 Thermal Cracking

Hydration process in substantial concrete is exothermic and it has low thermal conductivity, and That causes spatial and temporal thermal gradients, generating sufficient tensile stress that can result in undesired thermal cracking [24]. For thermal cracking, many such criteria have been proposed, including the ratio of failure stress-to-strength, strain rate, allowable temperature gradients and probabilistic methods of failure prediction [25]. Nevertheless, the application of each method has limitations. For example, the failure stress-to-strength ratio is not always the same because it changes according to the temperature history, the amount of restraint and the material properties of the material inherently [26]. Early age concrete exposed to harsh environmental conditions leads to cracking of concrete. Rapid water evaporation causes plastic shrinkage cracks, and heat buildup and low thermal conductivity produces thermal cracks. However, there are several methods to predict thermal cracking but all of them have limitations depending on the material and environmental factors. Thermal cracking in a concrete structure is shown in Figure 2.

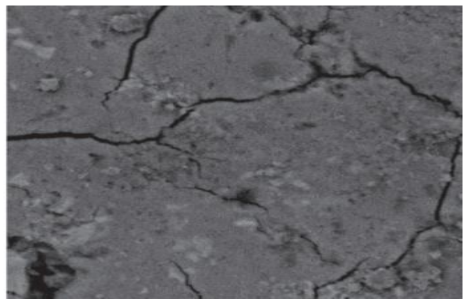

Figure 2 *Thermal Cracking in Concrete [27]*

3 Governing Parameters

Governing parameters for these cracks are as following:

3.1 Plastic Shrinkage Cracks

The main causes of plastic shrinkage cracking in concrete are environmental conditions and material properties affecting surface moisture loss rate prior to the concrete sets. Recent studies have found that evolution of the bulk modulus is the dominant plastic shrinkage parameter [19] [20].The rate of evaporation from the concrete surface is accelerated by elevated temperatures. Rapid drying at the concrete surface can cause plastic shrinkage cracks due to high evaporation rates [28]. When low water cement ratio or high fine aggregate content mixture is used, the bleeding may be less, so surface moisture is not sufficient which in turn results in shrinkage cracks [29]. Factors affecting plastic shrinkage cracking are shown in Figure 3.

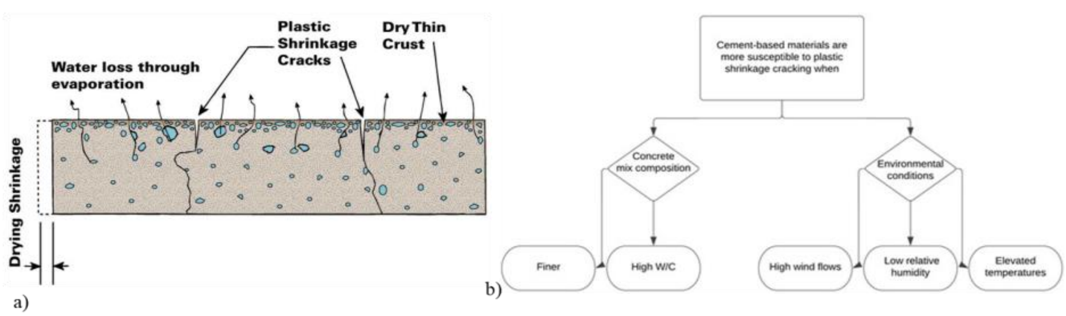

Figure 3 *Factors affecting plastic shrinkage cracking [30].*

3.2 Thermal Cracking

Temperature gradients within the concrete, commonly during the hydration process, can cause thermal cracking due to the formation of internal stresses that tend to crack the concrete. During the exothermic reaction of cement hydration, heat is generated, causing internal increase in temperatures resulting in thermal cracking [31].Higher Co-efficient of Thermal Expansion materials expand and contract more with temperature changes and therefore have a higher magnitude of thermal stress [32].Thermal stresses are influenced by the thermal expansion characteristics of the aggregates. High thermal expansion of aggregates such as quartz causes increased internal stresses and the possibility of cracking [33]. The temperature development as the hydration heat dissipates through the convection surfaces is shown in Figure 4.

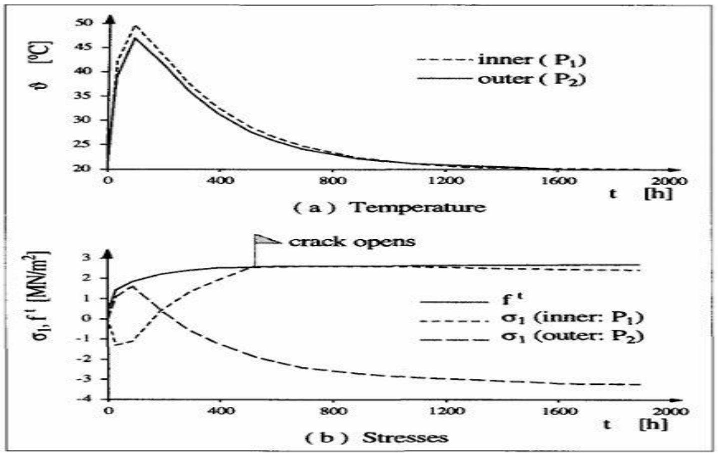

Figure 4 *Temperature and stress developments [34].*

Plastic shrinkage cracking is simply a rapid surface moisture evaporation that results from high temperatures and low water to cement ratios as well as insufficient bleeding. Internal temperature gradients during cement hydration cause thermal cracking, and materials with higher thermal expansion coefficients expand more than other materials, i.e., quartz, are more prone to cracking. Reduction of cracking in concrete depends on the proper management of these factors [35] [36].

4 Types of Fibers

4.1 Types of Fiber

By its nature, concrete is very strong in compression yet low in tensile so different fibers, metallic, synthetic, natural and inorganic are scattered in the matrix to improve tensile strength, control of cracks, toughness and durability [37]. The most common metallic alternative, steel fibers yield a dramatic increase in flexural strength, impact strength and energy absorption, but are susceptible to staining and are expensive to add. Of synthetics fibers, polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), nylon, and polyester are in common use; they effectively restrain plastic shrinkage and microcracking, improve ductility, and withstand alkaline conditions (e.g., PVA is highly chemically bonded and nylon swells in the presence of moisture) [38]. Different types of Fibers are used in concrete to reduce the cracks. Some of them with key benefits and description are shown in Table 1.

Table 1 *Types of Fibers [39] [40] [41] [42] [43] [44]*

Fiber Type	**Description**	**Key Benefits**
Steel Fibers	Discrete steel filaments that are short and added to the mix	Improve tensile strength, post-crack ductility, and fatigue resistance; limit crack width under loading
Polypropylene (PP) Fibers	Synthetic microscopic fibers	Control plastic and drying shrinkage; reduce permeability and surface crazing
Glass Fibers (Alkali Resistant)	Used in architectural panels like GFRC	Enhance flexural strength, crack bridging, and resistance to environmental degradation
Basalt Fibers	Derived from volcanic rock with high chemical resistance and modulus	Increase tensile strength, toughness, and thermal stability in mass concrete

Carbon Fibers	Extremely strong and stiff synthetic fibers	Boost tensile/flexural capacity; ideal for high-performance and rehabilitative structures
Natural Plant Fibers (e.g. jute, sisal, coir)	Renewable fibers from natural sources	Improve toughness, arrest cracks, and lower environmental impact of concrete
Nylon	Synthetic polyamide fibers with high elongation and durability	Enhance tensile and flexural strength, improve ductility, reduce shrinkage cracking, and increase impact resistance.

4.2 Properties of Fiber

In concrete, fibers can be described in terms of a number of critical properties that have a direct effect on their performance to improve the mechanical behavior of the cementitious matrix. Tensile strength is an important property, because fibers with high tensile resistance including steel fibers, carbon fibers, and aramid fibers, could act as crack bridging fibers and slow down crack propagation [45]. Strength of bonds between the fiber and the cement paste is also another important parameter; fiber which have a strong interfacial bonding helps to enhance energy absorption and ductility (this factor is true in fibers like polyvinyl alcohol (PVA)) [46]. Equally important, but often underemphasized, is the elongation at break, which measures how far a fiber can stretch before breaking. This is directly associated with the ductility of this fiber which further creates a greater deformation capacity of concrete when under stress. Fibers like polypropylene, polyethylene, nylon that have higher elongation to break provide the composite with the ability to deform without abrupt failures hence controlling the crack widening and better energy absorption [47]. Fiber performance under extreme surroundings is determined by thermal stability and corrosion resistance potential. Steel fibers are prone to corrosion and carbon and basalt fibers are more resistant to chemical and temperature forces [48]. Typical properties of common fibers are described in Table 2.

Table 2 *Typical Properties of Common Fibers [47]*

Fiber Type	Diameter (µm)	Specific Gravity	Modulus of Elasticity (GPa)	Tensile Strength (GPa)	Elongation at Break (%)
Steel	5-500	7.84	200	0.5-2.0	0.5-3.5
Glass	9-15	2.6	70-80	2.0-4.0	2.0-3.5
Polypropylene	20-400	0.9-0.95	3.5-10	0.45-0.76	15-25
Carbon	8-9	1.6-1.7	230-380	2.5-4.0	0.5-1.5
Nylon	23-400	1.14	4.1-5.2	0.75-1.0	16-20
Polyethylene	25-1000	0.92-0.96	5.0	0.08-0.6	3-100
Wood fibers	-	1.5	71	0.9	-
Sisal	10-50	1.5	-	0.8	3.0

4.3 Fiber Selection for cracks

The different fibers have been investigated regarding their ability in control of the shrinkage of plastic and thermal cracking of concrete. To minimize shrinkage of plastic, synthetic fibers such as polypropylene are largely applied because of their strong elongation and the character of development into a dense network within new concrete [14] [40]. Glass and natural plant fibers also have moderate advised effectiveness towards the control of early-age cracking [41] [44]. In the case of thermal cracking, basalt and carbon fiber offers a strong thermal stability and tensile strength which qualifies them to be used in high-performance concrete [42] [43]. But at the same time every alternative has its constraints, including less stiffness, low bond strength, brittle or degrades in the environment with time. Steel fibers are highly suitable for use in mitigating both plastic shrinkage and thermal cracking in concrete owing to their high tensile strength and thermal stability. They successfully bridge early microcracks and lower crack widths. Steel fiber-reinforced concrete improves crack resistance under both early-age shrinkage and elevated temperature conditions [49] [50].

5 Conclusion

Although concrete is extensively employed in construction and has great compressive strengths, it has basic disadvantages in that it has low tensile strength, low ductility, and prone to several types of cracking, especially plastic shrinkage and thermal cracking. These problems happen most commonly in challenging environment conditions where quick loss of moisture and thermal gradients create adverse effects on structural performance. This review discussed various types of fiber applied in mitigating these problems, which include synthetic fiber, glass, basalt fiber, carbon fiber and natural plant fiber. Each type offers different advantages: synthetic fibers help control shrinkage; glass and basalt fibers improve toughness and thermal resistance; and natural fibers provide eco-friendly reinforcement. Nevertheless, steel fibers always performed better than the other fibers regarding the mechanical strength, crack-bridging effect, exposure to environmental stresses. The presented evidence shows that steel fiber-reinforced concrete (SFRC) leads to a significant control of micro- and macro-cracks and increases post-cracking behavior and substantially mitigates occurrences of early-age and thermal cracking. Such characteristics make steel fibers a highly strong and dependable option to improve the long-term performance and durability of a concrete structure under harsh environments.

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