Properties of Fibers

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Fibers that are commonly used to reinforce the binding matrix in concrete are typically made of steel, basalt, carbon, polypropylene, polyvinyl alcohol (PVA), glass, and natural fibers.

fiber reinforcement synthetic fibers natural fibers alkali-activated binders

1. Introduction

Concrete with Ordinary Portland cement (OPC) binder is the most widely used material in the construction industry across the globe. Its high compressive strength, versatility, and relatively low cost made it the preferred choice in various ranges of construction applications. With the rise in urban development, the production of OPC reached four billion metric tons and is projected to increase in the next decade [1]. Producing one ton of cement requires approximately two tons of raw materials and emits nearly equal amounts of carbon dioxide emissions into the atmosphere [2]. The extensive utilization of cement in concrete aggravates global warming with adverse and long-term environmental impact. The utilization of industrial byproducts such fly ash, ground granulated blast furnace slag (GGBS), and silica fume reduces reliance on OPC, enhances concrete properties, and decreases the need for landfills. Other agricultural byproducts, such as rice husk ash, and treated materials such as metakaolin also decrease the reliance on OPC and enhance concrete properties. Concretes with alkali-activated binders mainly depend on the characteristics of the aluminosilicate precursor, the type and concentration of the alkaline activator solution, and the curing environment [3]. All types of concrete, including those with OPC and alkali-activated binders, are characterized mainly by their brittle nature and low tensile strength. These characteristics mainly lead to crack formation, poor durability, and high maintenance cost. Studies found that concretes with industrial byproducts have lower resistance to cracking and higher brittleness compared to OPC-based concretes [4].

The use of fibers as reinforcement in cementitious matrices has become increasingly common. Several studies proposed addressing the brittleness and low tensile strength in cementitious concrete composites by adding fibers. Fibers enhance the ability of concrete structures to withstand relatively higher levels of stress and strain while maintaining structural strength, stability, and durability [5].

The physical interactions between the reinforcing fibers and the concrete matrix enhance the ductility and crack resistance of fiber-reinforced concretes. The strength of the bond between reinforcing fibers and the cementitious matrix is essential to preventing crack propagation [6]. Fibers in concrete composites act as bridges within the concrete matrix through physical bond interactions. The bridging action through reinforcing fibers increases the energy required for a crack to propagate through concrete and enhances its crack resistance [7]. The impact of crack formation and growth on the mechanical properties and durability of concrete is effectively mitigated by the addition of reinforcing fibers [8]. As a crack propagates through the matrix, various interactions occur between the fibers and the surrounding material. These interactions encompass fiber bridging, de-bonding, pullout, and rupture [6][9][10]. Fiber bridging causes cracks to reduce the stress at the crack location. Meanwhile, the energy absorption during crack propagation is greatly influenced by fiber de-bonding and pullout at the interface. Fiber de-bonding happens when the bond between the fiber and the matrix weakens as the stress at the fiber–matrix interface exceeds the bond strength and results in loss of adhesion. Fiber pullout happens when fibers are partially or completely pulled out from the concrete matrix. Fiber rupture occurs when the fibers themselves break or rupture due to excessive tensile stress. This type of failure typically happens in high-strength fiber-reinforced concretes [11]. Therefore, the strength of the bond between the reinforcing fiber and the surrounding matrix determines the ability of fibers to effectively resist cracks [6].

Up to an optimum fiber content, often expressed as volume fraction, the addition of reinforcing fibers can significantly enhance the mechanical properties and durability of concrete. The volume fraction of fibers measures the volume occupied by the fibers in relation to the total volume of the composite. The extent of improvement in mechanical properties and durability was found to depend on the fiber type, geometry, and content, as well as the binder composition. The average space between fibers decreases as the fiber content increases, thereby limiting the initiation and propagation of cracks within the matrix. Steel fibers are the most investigated in terms of the effect on mechanical properties of concrete [7][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31]. They generally create a stronger bond with the matrix, leading to higher flexural and tensile performances compared to other types of fibers. Adding steel fibers up to a volume fraction of 1.75% enhanced the post-cracking behavior of alkali-activated GGBS/fly ash concrete, resulting in increased strength, toughness, and ductility [12]. Carbon fibers enhanced the flexural and compressive strengths of concrete, especially after exposure to high temperatures [32]. Adding polyvinyl alcohol (PVA) fibers up to a volume fraction of 1% reduced concrete drying shrinkage by approximately 60% [33]. Polypropylene, basalt, glass, and PVA fibers were also investigated in their various configurations [12][13][28][34][35][36][37][38][39][40][41][42][43]. Some studies have reported the effect of combining different fiber types, or blending different geometries of the same fiber, on concrete properties [12][16]. A hybrid combination of fibers may be formed by blending different types of fiber materials or different geometries/configurations of the same type, merged together at various contents.

Despite the enhancements in mechanical properties and durability, fiber reinforcement can negatively impact flowability and setting time of concretes. The influence can vary significantly based on fiber material type, dosage, and geometry as well as binder type. Rigid fibers form contact networks within fresh concrete composites, increasing their yield stress. When the fiber concentration surpasses a critical level, it causes the formation of fiber chunks or balls and uneven dispersion, impeding the flow of fluid matrices through these networks [18]. The rough surfaces of fibers such as crimped and hooked steel further compromise the workability of fiber-reinforced concretes. The flow of freshly mixed concrete is also affected by the orientation and distribution of fibers. It is important to highlight that an increase in the yield stress of fresh concrete due to incorporation of fibers results in a decline in compressive strength. Therefore, achieving an even distribution of fibers is essential to enhance the overall performance of the concrete [18]. Excessive fiber content introduces voids and defects into the concrete matrix, which affects its performance negatively. Monitoring the workability of fresh concrete is necessary to ensure the attainment of sufficient hardened strength after construction. Ulas [7] reported a sudden decrease in workability when rigid steel fibers content increased to 1.5% within slag-fly ash concrete. High content of steel fibers in concrete pushes aggregates apart, causing slump values to decrease substantially.

2. Properties of Fibers

Fibers that are commonly used to reinforce the binding matrix in concrete are typically made of steel, basalt, carbon, polypropylene, polyvinyl alcohol (PVA), glass, and natural fibers. Each type of fiber features unique characteristics that in turn produce concrete with various properties. **Table 1** shows typical mechanical and geometric properties of selected fibers. Many of the fiber types are characterized by substantial tensile strength, which allows them to effectively distribute loads and bridge across cracks.

Fibers can be classified as rigid or flexible depending on their elastic moduli. Rigid fibers are useful in preventing the propagation of cracks before they develop into macrocracks. Flexible fibers, on the other hand, reduce shrinkage cracking and enhance the durability of concrete composites. Steel, carbon, and glass are considered rigid fibers, while polypropylene, PVA, and nylon are considered flexible fibers. The elongation at breakage is another indicator of the ability of fibers to undergo significant deformations before breaking. Fibers with high elongation percentage such as polypropylene and PVA are flexible and more ductile [44][45].

Steel fibers are commonly used in reinforced concrete due to their high tensile strength and modulus of elasticity, which may reach 2.2 GPa and 200 GPa, respectively [46]. The addition of steel fibers to concrete enhances its tensile and flexural strengths, allowing the concrete to withstand strains, absorb energy, and resist cracking even at high temperatures [20][21][47][48]. Steel fibers can be manufactured in various shapes including straight, crimped, and hooked. They also come in a wide range of cross-sectional shapes including circular, rectangular, or square [49]. Hooked steel fibers provide the most effective improvement in the tensile and flexural strengths of concrete compared to straight and crimped types [20][49]. Steel fibers are cost effective in many parts of the world, but their production contributes to significant CO_2 emissions. Carbon fibers are characterized by tensile strength as high as 3.5 GPa and are therefore used for making fiber-reinforced polymer (FRP) sheets for retrofitting reinforced concrete structures [50]. Carbon fibers have a high melting point of approximately 3650 °C and are considered chemically stable, making them suitable for high-temperature applications and chemically aggressive environments [51].

The incorporation of basalt fibers in concrete enhances its compressive strength and energy absorption capacity. Basalt fibers are cost effective and require a relatively lower amount of energy for their production. Their high tensile strength, low density, and resistance to high temperatures make them suitable for use in various industries [52][53]. Because polypropylene fibers are hydrophobic, they may contribute to the durability of concrete by making structural elements less susceptible to water infiltration [51][53]. However, this hydrophobic nature may weaken their bond with the concrete matrix. Polypropylene fibers have a relatively low modulus of elasticity and a low melting point [51]. These characteristics might limit their use in certain applications related to the construction industry.

However, melted polypropylene fibers create channels that not only prevent the spread of fire but also release internal pressure [51]. Polypropylene fibers are highly ductile, with 25% deformability before breakage [44].

Glass fibers offer high tensile strength and high strength-to-weight ratio, which make them suitable for producing lightweight yet strong structural elements. They have been incorporated into different binder compositions for the production of concrete because of their low density, high durability, and good thermal insulation properties [36][54][55][56][57]. However, they reportedly have relatively poorer resistance to moisture and abrasion. Glass fibers are categorized as C-glass, D-glass, R-glass, E-glass, S-glass, and AR-glass [56][57]. Due to its cost-effectiveness, E-glass is the most commonly used type in concrete composites. C-glass fibers are utilized in concretes exposed to acidic environments, while AR-glass is used in concrete with alkali-activated binders due to their ability to resist corrosive effects of alkalis [56]. The production process involves melting broken glass at elevated temperatures, which is then formed into different types of glass fiber products [57].

PVA fibers are hydrophilic and have low density and high resistance to acids and alkalis. Their high elastic moduli and strong adhesion to cementitious matrix make them effective in controlling shrinkage [33][40]. PVA fibers were shown to improve the flexural and compressive strengths of concrete due to the strong bond with the matrix [33][40].

Natural fibers are usually sourced from natural resources such as plants. They are characterized by their low density, availability, and relatively low cost. Plant-based natural fibers, such as flax, jute, cotton, and sisal, were extensively studied [58][59][60][61]. A common significant limitation is their moisture sensitivity, especially plant-based fibers such as cotton and sisal, which can lose strength when exposed to moisture. Furthermore, natural fibers generally exhibit lower tensile strength and stiffness compared to synthetic counterparts, limiting their use in applications requiring high strength or rigidity [62].

The type, content, and geometry of fibers play a critical role in shaping the properties of concrete composites, such as tensile strength, compressive strength, energy absorption capacity, bond-slippage behavior, and crack formation [38][63][64]. Studies have shown that an optimal fiber content exists, depending on fiber type, for concrete mixes to achieve peak fresh properties and hardened concrete to exhibit optimum mechanical strength. With appropriate mixing, water content, binder content, and superplasticizer, a homogeneous concrete mix can be attained up to a particular maximum fiber content, where the significantly higher tensile strength of fibers enhances concrete flexural strength. However, excessive fiber content can lead to poor compaction, increased porosity, and reduced flexural strength [13][32][65]. Random distribution of fibers may decrease the reinforcing efficacy of fibers to 54% compared to perfectly aligned fibers [63]. The bridging mechanism of fibers operates at both micro and macro-levels [15][63]. At the micro-level, they arise from the adhesion and interactions between fibers and the matrix. When a crack approaches a fiber, it requires energy to de-bond the fiber from the matrix. If the interfacial contact zone is inadequate in length or strength, the fiber may de-bond from the matrix. Consequently, cracks can either form, deflect within the material, or branch out into multiple smaller cracks [63].

Table 1. Physical properties of different types of fibers.

Fiber Type	Typical Geometric Properties	Density (g/cm^3)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Elongation (%) at Breakage	Melting Temperature (°C)
Steel	6 mm to 13 mm × 0.75 mm diameter [14]	7.88 [46]	200 [46]	2200 [46]	3 [46]	1200 [66]
Carbon	10 mm × 0.015 mm diameter [67]	1.78 [50]	230 [50]	3500 [50]	1.5 [50]	3650 [68]
Basalt	6 mm × 0.013 to 0.02 mm diameter range [69]	2.63 [70]	79.3 [70]	3000 [70]	3.1 [70]	1100 [71]
Polypropylene	8 mm × 0.033 mm diameter [12]	0.91 [12]	2.8 [44]	500–700 [44]	25 [44]	165 [72]
Glass	12 mm × 0.02 mm diameter [59]	2.5 [55]	82 [55]	2500 [55]	3 [55]	800 [73]
Polyvinyl alcohol (PVA)	8 mm × 0.04 mm diameter [67]	1.3 [45]	42 [45]	1600 [45]	7 [45]	280 [74]
Polyethylene	12 mm × 0.02 mm diameter [75]	0.97 [76]	116 [76]	2900 [76]	2.42 [76]	150 [77]
Jute	35 to 40 mm × 40 to 350 µm diameter range [58]	1.3–1.46 [58]	10–30 [58]	393–773 [58]	1.5–1.8 [58]	140 [78]
Sisal	35 to 40 mm × 50 to 300 µm diameter range [58]	1.45 [58]	38 [58]	600–700 [58]	2–3 [58]	300 [79]

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