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Review

A Review on the Effects of Waste Textile Polymer Fiber on Concrete Strength: Exploring the Key Parameters

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Abstract: The construction industry is one of the largest users of natural resources and can, thus, lead to significant environmental issues. Therefore, there is elevated interest worldwide in developing sustainable construction materials and techniques that can reduce these associated environmental impacts. In this context, one substantial area of focus is the incorporation of textile waste in construction materials, such as concrete. Textile waste is generated in large quantities from the production stage through to the consumption and end-of-life disposal periods. Hence, it is prudent to devise effective ways of recycling this waste, which can, in turn, reduce the environmental implications of textile production and cut down the quantity of waste sent to landfills. Furthermore, fibers obtained from recycled textile waste can be used to reinforce concrete, thus replacing the need for synthetic fibers. This review focuses on the use and effects of incorporating polymer fibers from recycled textile waste in concrete and the use of textile polymer fiber in the construction of various structures, and challenges in the use of recycled fibers in concrete and the parameters affecting the resultant strength of concrete structures, such as stress transfer, crack control, bond strength, and spalling, etc., are discussed.

Keywords: concrete strength; textile fibers; waste management; building materials

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1. Introduction

Serious environmental issues are constantly smothering our biosphere, and, therefore, pollution control and waste management have become quite critical for the survival of the human race as a whole in the longer term [1]. Suitable waste management approaches are, thus, vital for protecting the environment from imminent devastation and preserving its natural resources [2]. In this context, recycling is a critical element of waste management, as it concomitantly decreases the amount of waste and conserves natural resources by reusing existing materials to produce newer products [3]. Recycling can also cut down the cost and energy in exploring novel raw materials. For instance, recycling textile waste is an effective waste management technique that can also reduce the amount of waste that ends up in landfills [4]. The use of textile waste in concrete is an emerging field of research that aims to address the problem of textile waste to some extent, while it also can result in enhancing some of the properties of the modified concrete structure [5]. In addition, the durability and strength of concrete elements can be improved through the incorporation of recycled waste materials, thereby making them more resistant to wear and tear, weathering, and corrosion.

Concrete is a renowned and prevalent building material that is used worldwide in the construction sector, and is made by mixing cement, water, and aggregates [6]. Aggregates help to control the shrinkage and expansion of the concrete due to temperature changes, moisture variations, and chemical reactions. Aggregates are indispensable in concrete production due to their contributions to strength, durability, cost-effectiveness, workability, stability, aesthetics, and environmental sustainability. Replacing some of the ingredients for making concrete with recycled waste, even in nominal amounts, can lead to a reduction in the amount of cement and/or aggregate in the mix designs [7–10]. Cement, the crucial component of concrete, is a significant contributor to global carbon dioxide (CO_2) emissions [11–13]. According to various studies, one ton of cement production causes the formation of a significant amount of CO_2 emission (Figure 1A). Even though numerous efforts are being made to reduce CO_2 emissions in cement production, this remains a challenging task because of the global demand for cement [14–16]. Therefore, the transition from conventional methods to more sustainable cement production methods is essential for solving this crisis. Employing technologies and innovations in low-carbon concrete production, including alternative cementitious materials, carbon capture and utilization/storage techniques, and energy-efficient manufacturing processes, can utilize some of these alternative methods. Identifying gaps in understanding the scalability, cost-effectiveness, and environmental performance of these technologies is also crucial. Conducting lifecycle assessments of different concrete materials, quantifying their environmental impacts from raw material extraction to disposal, and assessing factors such as GHG emissions, energy consumption, water usage, and waste generation can significantly impact low-carbon concrete production. Exploring circular economy principles in the construction sector, emphasizing waste valorization, material reuse, and circular supply chains, can also be a game-changer. Analyzing existing policies, regulations, and incentives related to sustainable waste management and low-carbon concrete solutions at the local, national, and international levels, identifying gaps in policy implementation and enforcement, and assessing the potential barriers and opportunities for scaling up sustainable practices within the industry can also help with the sustainable development of the low-carbon concrete industry.

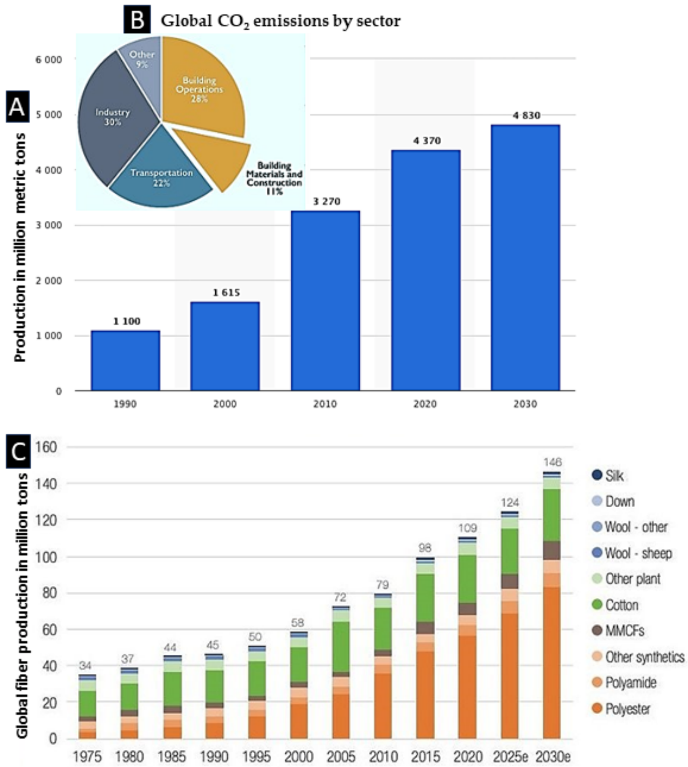

Figure 1. (**A**) Graph showing the cement production 1990–2030 (https://www.globalefficiencyintel.com/new-blog/tag/carbon+capture, accessed on 6 February 2017), (**B**) Graph showing the global CO_2 emission by sector https://nickelinstitute.org/blog/2020/april/functional-facades-help-tackle-building-emissions/, accessed on 21 April 2020, (**C**) graph showing the textile fiber production 1975–2030 (https://www.textiletoday.com.bd/demand-for-preferred-fibers-growing-rapidly/, accessed on 23 August 2021).

Textile production is another industry that contributes to significant CO_2 emissions (Figure 1B). Hence, textile recycling and the adoption of circular economy principles can significantly cut down CO_2 emissions [17]. In recent years, the construction industry has also witnessed the emergence of a revolutionary and eco-friendly approach to producing sustainable and fiber-reinforced concrete material by incorporating recycled textile waste [18]. The resultant concrete has several unique properties, such as improved reinforcement, tensile, and flexural strengths, and enhanced durability, while also having reduced degrees of shrinkage and cracking upon spalling. Textile matrices can also be used as a replacement for traditional coarse aggregates, thus reducing the overall weight of the concrete and making it relatively lightweight. In addition, textile waste can be used in various forms, such as fibers or aggregates, in the production of concrete structures [19]. Furthermore, the incorporation of textile waste can reduce the amount of cement in the concrete mix, which leads to cost-effective production while mitigating the associated environmental issues. Textile waste is generally produced in every stage of textile production, including pre-consumer waste created during the spinning, weaving, dyeing, and finishing of clothes, as well as post-consumer waste [20,21]. Fibers derived from textile waste have been used in concrete for decades to improve its mechanical properties, such as tensile strength, toughness, and durability. These fibers are typically made from cotton, rayon, polyacrylates, polypropylene, polyesters, and nylon. Numerous studies have been also conducted to explore the use of textile waste in concrete [22–26]. Generally, the use of textile waste in concrete can be a sustainable and innovative solution to both the textile waste problem and the scarcity of durable and eco-friendly construction materials. However, more research is needed to unequivocally determine the optimal forms and proportions of textile waste to use in concrete, as well as the long-term durability of such concrete.

2. Fibers in Textile Materials: General Considerations

Cotton, wool, silk, linen, hemp, jute, ramie, coir, cashmere, mohair, angora, alpaca, camel hair, and vicuna are some of the natural fibers used in the textile industry, while artificial fibers are mainly rayon, modal, tencel, and synthetic polymer fibers [27–32]. Based on the mechanical properties, textile fibers can be categorized into two groups, such as low-end fibers and high-end fibers. Low-end fibers are those with a relatively low tensile strength (<5 GPa) and elastic modulus (<200 GPa), but high ductility (>5%). High-end fibers, on the other hand, have a high tensile strength and elastic modulus but are brittle [33]. Most of these high-end fibers are utilized for special-purpose applications, such as making bulletproof or fire-resistant garments. Usually, they have an elongation of less than 2% under an applied force, can withstand up to 2–5.6 GPa tensile force, and their moduli of elasticity are in the range of 70–500 GPa. Some examples of high-end fibers are Kevlar, carbon fiber, and glass fiber. Nanocellulose is another similar fiber type with comparable properties with counterparts. Comparing the requirements of the application to the cost of the material, high-end fibers are not generally preferred for building and structural applications. In the low-end textile fiber group, cotton, wool, silk, and jute are highly compatible for making thermal and sound-insulating elements rather than reinforcing elements owing to their porous and lightweight characteristics [34]. On the other hand, synthetic polymer fibers can be considered for both building and structural applications due to their reinforcement properties when incorporated into concrete elements. A comparison between the natural and synthetic fibers used in concrete is listed in Table 1.

Synthetic Polymer Fibers

Synthetic polymer fibers, which are produced through the polymerization of monomers and spun into fibers, are an essential component of the textile industry due to their versatility and wider range of applications [35]. Their ability to be manufactured in different forms, such as long continuous strands of fiber called filament yarns or short-length staple fibers, make them suitable candidates for the textile industry [36,37]. This flexibility in manufacturing has led to a wide range of textile products being produced by using polymer fibers.

Their ability to tune the properties makes them more suitable for specific applications such as flame-resistant, water-repellent, or antimicrobial clothing applications. The different types of these polymer fibers include polyester, polypropylene, nylon, and polyacrylic fibers [38–47]. Polyester fibers are recognized for their robustness, wrinkle resistance, and moisture resistance, which make them an optimal choice for making different types of garments and high-visibility vests [48,49]. These can also be blended with other fibers to tune their properties, such as stretchability and softness. Polypropylene is a lightweight polymer fiber that is often used in the production of outdoor and active wear due to its water/stain/fungus resistance properties, thus making it a popular choice for outdoor applications [50,51]. Nylon, on the other hand, has a high strength, low abrasion, and elasticity, which make it ideal for manufacturing athletic wear, hosiery, and other garments that require stretchability and sturdiness [52,53]. Polyacrylonitrile fiber is generally considered as a lightweight fiber that is often used as a substitute for wool due to its softness and warmth, thus making it ideal for producing blankets and other comfortable textiles [54,55]. When it comes to recycling polymer fiber from textile waste, there are two main approaches; the first one is mechanical recycling, in which textile waste is broken down into small fibers or pellets by shredding or chopping, and then processed into fibers/pellets, then to yarns/fabrics or other products [56,57] The second approach is chemical recycling, where large polymer chains are broken down chemically into individual monomers [58–60]. While this approach is more effective in producing high-quality recycled fibers, it can be more complex and expensive than mechanical recycling. When textile products are made up of different fibers and materials, it is also difficult to separate and recycle them effectively. However, advanced technologies for sorting and separation can help to make this process more efficient.

Table 1. Advantages of natural and synthetic fibers in concrete.

Advantage	Natural	Synthetic
Sustainability: Both are sustainable solutions for concrete reinforcement and waste management [20,29]	☑	☑
Reduced Carbon Footprint: Natural fibers have a lower carbon footprint compared to synthetic fibers since their production requires less energy and emits fewer greenhouse gases [61].	☑	
Improved Crack Control: Both types of fibers can enhance the crack control properties of concrete by reducing the crack width and preventing crack propagation. They help in distributing stress and improving the tensile strength of the material [62,63]	☑	☑
Impact Resistance: Concrete reinforced with both types of fibers exhibits improved impact resistance, making it more suitable for applications where impact loading is a concern [64,65]	☑	☑
Acoustic Insulation: Natural fibers have inherent thermal and acoustic insulation properties, which can help in reducing heat transfer and sound transmission through concrete structures [66].	☑	
Strength and Durability: Natural fibers generally have a lower tensile strength compared to synthetic fibers. This can limit their effectiveness in providing high-level structural reinforcement or in applications requiring exceptional durability [67]		☑
Less Moisture Sensitivity: Synthetic fibers exhibit less moisture sensitivity while natural fibers tend to absorb moisture, which can affect their mechanical properties and durability over time. Moisture absorption can lead to fiber swelling, reduced bond strength, and potential fiber degradation [68]		☑
Less Degradation and Biodegradability: Synthetic fibers have more stability toward biodegradation, while some natural fibers are prone to biodegradation, especially when exposed to moisture, microorganisms, or harsh environmental conditions. This can lead to reduced fiber strength and compromised long-term performance [69]		☑

Table 1. *Cont.*

Advantage	Natural	Synthetic
Non-Variable Properties: Natural fibers can exhibit variations in their properties, including fiber length, diameter, and mechanical characteristics, due to factors such as plant species, growth conditions, and harvesting techniques. This variability can make it challenging to achieve consistent and uniform reinforcement in concrete, but synthetic fibers have more stability [70]		☑
Cost: Synthetic polymer Fibers can be more expensive compared to natural fibers, increasing the material cost of concrete. The cost-effectiveness of using synthetic polymer fibers needs to be considered in relation to the specific project requirements and performance benefits [71]	☑	
Compatibility and Bonding: The compatibility of fibers and the cementitious matrix is important to ensure proper bonding and effective reinforcement. Surface treatments or modifications may be required to enhance the fiber–matrix interaction and bond strength [72]		☑
Improved Workability: The addition of synthetic polymer fibers can improve the workability of concrete compared to natural fiber, making it more cohesive and reducing the occurrence of segregation and bleeding [72]		☑
Environmental Impact: Synthetic polymer fibers are derived from non-renewable petrochemical resources, and their production and disposal contribute to environmental concerns. The recycling options for used concrete containing synthetic polymer fibers may also be limited [73]	☑	
Ease of Mixing and Placement: Synthetic polymer fibers are generally easy to mix and distribute within concrete mixes. They disperse uniformly and require minimal compaction effort, facilitating ease of placement [74]		☑
Chemical Resistance: Polymer fibers have a good resistance to chemical attacks, including exposure to alkaline environments, chlorides, and other aggressive substances. This enhances the durability of concrete in chemically aggressive environments [75,76]		☑

3. Use of Textile Polymer Fiber in the Construction of Various Structures

3.1. Fiber in the Construction of Beams

The construction of beams, columns, corbels, and walls requires concrete with a high tensile strength, crack resistance, durability, load-carrying capacity, and shear strength. The incorporation of recycled fibers can affect the concrete properties in two ways. Some of these properties can undergo enhancements, while others can be diminished by adding fiber into concrete. Creating a balance and optimizing the composition can, therefore, form a better concrete mix with enhanced strength and other favourable characteristics. In beams, fibers play a crucial role in enhancing tensile strength and crack resistance. Textile polymer fibers can be effectively used to reinforce concrete beams, especially in applications where a high flexural strength and durability are required. These fibers help in distributing loads, reducing shrinkage cracks, and improving the overall structural performance. Shitao Cheng et al. proposed that the crack resistance and flexural capacity of textile–FRC composite beams can be increased by 79.56% and 39.04%, respectively, under specific conditions compared to ordinary concrete [77]. Alice Johny et al. found that jute and bamboo textiles incorporated in concrete beams improved their tensile strength load-carrying capacity [78]. In certain instances, samples incorporating natural fibers demonstrated a remarkable 90% increase in tensile strength, representing a substantial improvement when compared to the control sample. The experimentation highlighted a delayed onset of crack formation in beams, indicating the reinforcing effect of natural fiber composites and their positive impact on structural performance enhancement. Moreover, the beams showcased enhanced load–deflection behavior, implying efficient load distribution and dissipation within the composites, thereby bolstering their load-bearing capacity.

3.2. Fiber in the Construction of Columns

When it comes to columns, the inclusion of fibers helps to control cracking due to shrinkage and temperature changes, enhancing the longevity and durability of concrete columns, particularly in high-rise structures or areas prone to seismic activity, and some studies have explained this. In his research, Kiang Hwee Tan [79] concluded that the improved strength observed in concentrically loaded columns when bonded with external fiber-reinforced polymer systems can be attributed to two primary factors. Firstly, the transverse fibers exert a confinement effect on the concrete, leading to an increase in its uniaxial compressive strength. This, in turn, enhances the contribution of the concrete to the column's load-carrying capacity. Secondly, the longitudinal fibers directly contribute to bolstering the load-carrying capacity of the column. Hany Tobbi et al. discuss the strength model for concrete columns reinforced with polymer bars and ties [80]. Their experimental result, which was verified against experimental results and other models, showed that FRP ties significantly increased the concrete strength and ductility.

In another publication by the aforementioned research group [81], they delve into the behavior of concentrically loaded fiber-reinforced polymer concrete columns, examining various reinforcement types and ratios. The findings support the effectiveness of exclusively reinforcing columns with FRP when subjected to concentric loads. Specifically, columns reinforced internally with a combination of steel longitudinal bars and FRP transverse reinforcements exhibited enhancements in compressive strength and ultimate axial strain. Additionally, the use of FRP transverse reinforcement not only improved the column's corrosion resistance, but also provided an additional 10 mm (0.4 in.) of cover to the steel, further enhancing its durability.

3.3. Fiber in the Construction of Corbels

Corbels, which are structural elements projecting from a wall to support loads, can benefit from fiber reinforcement. Textile polymer fibers can enhance the shear strength and resistance to cracking in corbels, especially at the junctions with beams or walls where stress concentrations occur. This reinforcement improves the structural integrity of corbels under various loading conditions. Rafael Alves de Souza and colleagues [82] conducted a study on enhancing the strength of a damaged concrete corbel within an industrial biomass boiler. They implemented a local repair approach using a polymeric mortar, followed by reinforcement using carbon fiber-reinforced polymer (FRP) sheets. This intervention was tailored to meet the specific requirements dictated by the on-site conditions and design plans. The repair and strengthening measures effectively confined the concrete area affected by spalling, providing additional protection for the primary tie reinforcement of the corbel. Furthermore, the external wrapping (jacketing) technique significantly increased both the strength and ductility of the corbel. Eyad Sayhood and colleagues investigated the improvement in the load-carrying capacity of reinforced concrete corbels strengthened with carbon-fiber-reinforced polymer (CFRP) strips under either monotonic or repeated loads [83]. They observed notable enhancements in the load-carrying capacity of corbels strengthened with 50 mm strips when subjected to monotonically applied loads, with increases of 11%, 15%, and 27% observed for horizontal, inclined, and mixed orientations, respectively. The diagonal CFRP strengthening effectively controlled the widening and propagation of shear cracks, resulting in a clear increase in the load-carrying capacity of the corbels. In another research paper [84], an experimental investigation was conducted on the behavior of externally strengthened short-reinforced concrete corbels using carbon-fiber-reinforced polymer (CFRP) fabrics. The study examined the influence of various parameters on the structural performance of the corbels, including the quantity of internal secondary steel bars and configurations of the external composite sheets. The results from static load testing revealed a significant increase of up to 27% in the load-bearing capacity when external CFRP composite reinforcement was applied compared to control samples. The CFRP reinforcement effectively constrained the widening and propagation of shear cracks, leading to an improved load capacity and axial toughness of the corbels.

3.4. Fiber in the Construction of Deep Beams

Deep beams, characterized by their larger depth-to-span ratio, often experience significant shear and flexural stresses. Incorporating fibers, such as textile polymer fibers, can effectively strengthen these deep beams by improving their shear resistance, crack control, and overall structural performance. This reinforcement is especially valuable in buildings or bridges, where deep beams are used to transfer heavy loads. Mustafa Raheem and Hayder Rasheed, in their study, investigated the potential of using externally bonded FRP reinforcement for the shear strength enhancement of deep beams [85]. They found that CFRP flexural sheets increased the shear capacity of the deep beams tested by a significant margin, similar to the effect of longitudinal steel, and the improvement in the ultimate shear strength over the control beam depended on the orientation of the GFRP sheets. Elsayed Ismail reported the potential use of externally bonded carbon-fiber-reinforced polymer (CFRP) composite sheets as a strengthening solution to upgrade reinforced concrete (RC) deep beams with openings [86]. The study reported that the CFRP shear strengthening around the openings of the RC deep beams remarkably increased the beam strength. The structural response of the RC deep beams with openings was dependent on the degree of the interruption of the natural load path. Externally bonded CFRP shear strengthening around the openings was found to be very effective in upgrading the shear strength of the RC deep beams. The shear strength gain caused by the CFRP sheets was in the range of 66–71% when the opening was located at the mid-point of the shear span.

3.5. Fiber in the Construction of Walls

Fibers, including textile polymer fibers, can be beneficial in the construction of both load-bearing and non-load-bearing walls. These fibers enhance the tensile and flexural strength of concrete walls, reducing the risk of cracking and improving durability. Fiber-reinforced walls also exhibit a better resistance to impacts, vibrations, and environmental factors, making them suitable for various construction applications. Konstantinos K. Antoniades et al. [87] discuss the possibilities of how fiber-reinforced polymers can help to strengthen seismically damaged reinforced concrete walls. They studied the effect of damaged walls with an aspect ratio of 1.5. By using FRP jackets, the shear strength of RC walls subjected to seismic loads could be increased, and shear cracking was effectively controlled. Another article [88] also reported that the use of FRP jackets increased the shear strength of a repaired wall, controlled shear cracking, and reduced shear displacement. The repair of damaged RC walls using FRP can restore the performance of damaged RC walls, while also serving as a repair method of relative ease. In another study [89], it was found that the use of fiber-reinforced polymer (FRP) confinement and mechanical anchorages resulted in an increased axial capacity for walls with both small and large openings. Strengthening with FRP led to a substantial enhancement in the axial strength of specimens with small and large openings, showing improvements of 34–50% and 13–27%, respectively, compared to unstrengthened specimens. Additionally, the application of FRP strengthening prevented the buckling of the reinforcement and the occurrence of explosive failure modes, phenomena observed in unstrengthened specimens.

4. Effect of Incorporation of Fibers in Concrete

4.1. Stress Transfer and Load Distribution in Concrete Structures

Fibers can act as stress transfer elements within a concrete element by transferring the load from one part of the structure to another. This improved load distribution often minimizes localized stress concentrations, thus reducing the risk of premature failure [90]. The incorporation of textile fibers in concrete can also have a positive effect on both the flexural and impact strength. The reinforcement effect of fibrous components improves the material's ability to resist bending forces, thus increasing its flexural strength and preventing premature structural failure. Therefore, this improved flexural strength makes concrete suitable for applications that require a higher load-bearing capacity and enhanced structural performance. Concrete structures often experience impact loads, and the addition of fibers can enhance their impact resistance in such instances. This is depicted in Figure 2. Fibers, once dispersed throughout the concrete matrix, can absorb and dissipate the energy from impacts, thus reducing the formation and propagation of cracks. This improvement in impact resistance is particularly valuable in applications where dynamic or sudden loading is expected, such as industrial floors, pavements, and earthquake-resistant structures.

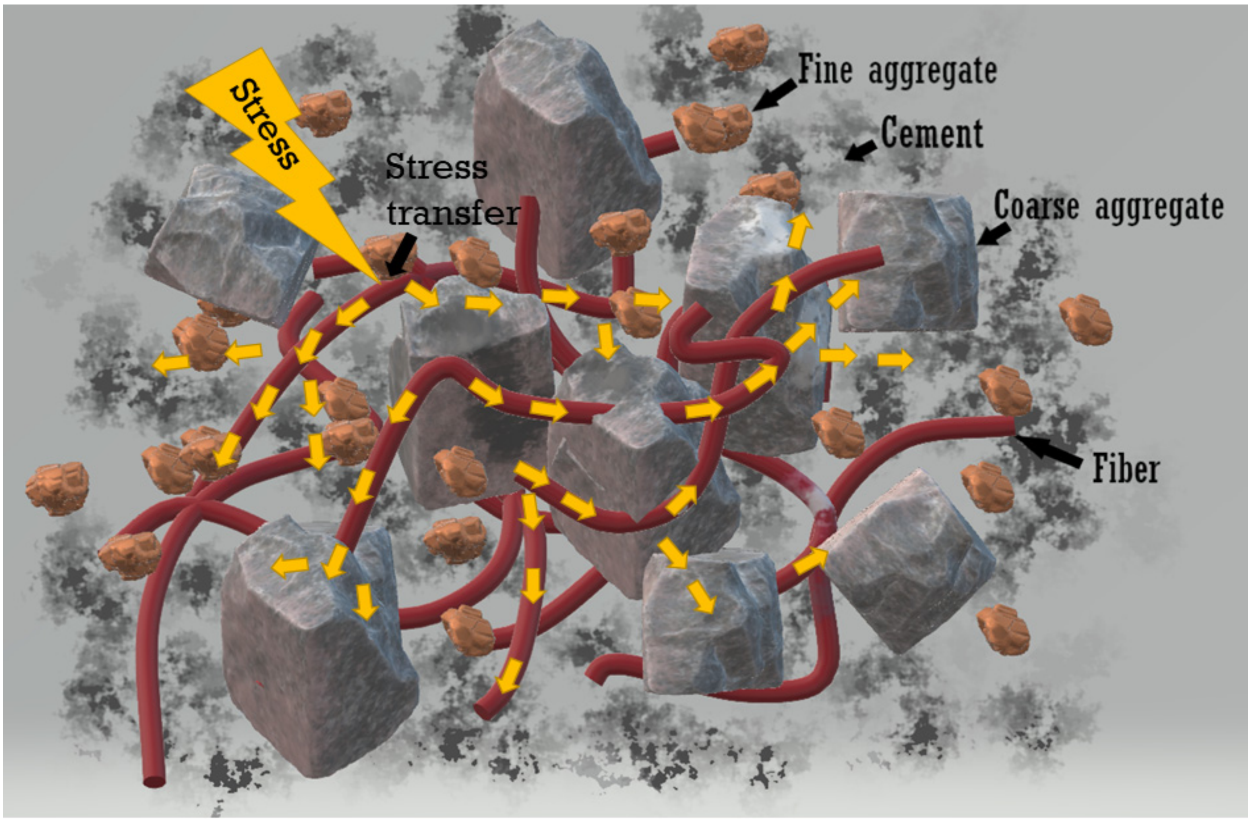

Figure 2. Stress transfer and load distribution in fiber-reinforced concrete.

In their study, Lichun Bian et al. noted that an increase in the elastic modulus results in higher stress values on fibers. Specifically, a larger elastic modulus of the interfacial layer between the matrix and fiber leads to elevated stress levels on the fibers. This highlights the crucial role of the interfacial layer in enhancing the stress transfer within the material [91]. In their research, Aktham H. Alani and colleagues investigated the impact of incorporating PET fibers and a ternary blended binder on the flexural and tensile behavior of concrete. Their findings indicated that stress values and strain capacity demonstrated an increase when PET fibers were added to the concrete mixes, compared to non-fiberized concrete mixtures [92].

4.2. Crack Control and Flexural Strength

Selecting a suitable fiber according to the requirement, dosage, and distribution of fibers within the concrete matrix can significantly affect the resulting mechanical properties. An optimal fiber dosage also depends on factors such as the desired strength improvement, fiber type, and concrete mix design. Adequate mixing techniques and a proper fiber dispersion often ensure a homogeneous distribution of fibers, thus allowing them to effectively reinforce the concrete matrix and maximize their contribution to the flexural and impact strength. The addition of fibers in concrete can also exhibit synergistic effects when combined with other additives or admixtures. Generally, a good degree of compatibility between fibers and other concrete components is essential to achieving the optimal performance and durability. The addition of fibers to concrete generally provides reinforcement within the matrix, thus effectively arresting crack propagation. Fibers can also act as a physical barrier that can, in turn, inhibit crack growth by bridging across the crack surfaces. This bridging effect aids in distributing the stress more evenly, subsequently resulting in preventing crack widening and limiting crack length. Textile fibers can help to enhance the toughness and ductility of concrete by absorbing energy during crack formation and propagation. Fiber reinforcement also plays a vital role in reducing the width and depth of cracks, thus enhancing the crack control capabilities of concrete. Ming Li et al. quantified the effect of recycled nylon fibers on the geometry of the crack and water flow behavior of cracked concrete [93]. The crack surface became rougher with an increase in the fiber dosage and the water permeability decreased.

In their study [94], SHEN Junmin and ZHANG Yancong explored the fiber-reinforced mechanism of composite fibers in cement concrete, focusing on the effects of composite fibers, such as polyacrylonitrile-based carbon fiber, basalt fiber, and glass fiber, on micro-cracks and the distribution of these fibers. They observed that composite fibers could significantly enhance the toughness index of fiber-reinforced concrete (FRC), with an increment rate exceeding 30%. The formation of a mesh structure by these composite fibers promoted concrete stability and ensured excellent mechanical properties. Furthermore, they noted that the compressive and bending strength of the FRC improved with an increasing content of polyacrylonitrile-based carbon fiber. The toughness index of the FRC was also found to surpass that of ordinary concrete. Polyacrylonitrile-based carbon fiber primarily served as the main skeletal component in the FRC, while basalt fiber and glass fiber filled in the concrete skeleton, forming the mesh structure. This arrangement facilitated cement hardening around the concrete matrix, thereby enhancing toughness and crack resistance in the FRC.

Elastic Modulus

When fibers are properly incorporated into concrete, they can contribute to the improvement in the elastic modulus in certain cases. The effect of fibers on the elastic modulus usually depends on several factors, including the type, length, and volume fraction of the fibers, as well as on their distribution within the concrete matrix. Zhang et al. investigated the flexural properties of basalt-fiber-textile-reinforced concrete sheets, including short AR-Glass fibers and the effects of the number of textile layers and fiber length on the flexural properties [95]. The results showed an improvement in the mechanical properties upon fiber addition in the concrete compared to the control sample. Different types of fibers, such as steel, polypropylene, glass, or carbon fibers, have varying mechanical properties and stiffnesses. Generally, fibers with a higher modulus of elasticity, such as steel or carbon fibers, can enhance the overall elastic modulus of the composite material compared to control specimens. The length and volume fraction of fibers can also significantly influence the elastic modulus of a composite material. Longer fibers and higher volume fractions generally provide greater reinforcement and lead to an increase in the elastic modulus. A uniform distribution of fibers within the concrete matrix is also important for achieving a more consistent improvement in the elastic modulus. Proper mixing techniques and adequate fiber dispersion often help to ensure a homogeneous distribution of fibers, thus leading to a better load transfer and reinforcement throughout the material. Rostami et al. reported on the effect of concrete alkalinity on the behaviour of reinforcing polyester and polypropylene fibers. From their observations, concrete samples that were reinforced with polymer fibers exhibited lesser crack formation and propagation in comparison to reference concrete [96]. Xingyi Zhu et al. studied [97] the effect of the interfacial transition zone on the Young's modulus of carbon-nanofiber-reinforced cement concrete. They found that, compared with plain cement concrete, CNFs can greatly enhance the mechanical properties of the interfacial transition zone, which will, in turn, improve the Young's modulus and stiffness of the cement concrete significantly. An increase in the Young's modulus of the interfacial transition zone resulted in a corresponding increase in the Young's modulus of the cement concrete. This can be attributed to its role as a robust connection between the cement mortar and aggregates, enhancing the overall structural integrity and stiffness of the concrete.

4.3. Bond Strength

The incorporation of textile fibers in concrete can have a positive effect on the bond strength within its matrix. These fibers often act as a bridge between the cementitious matrix and other materials, such as reinforcement bars or overlays, thus promoting interfacial adhesion [98]. This type of bridge formation generally enhances load transfer and prevents bond failure by increasing the contact area and improving the stress distribution across the interfaces. Furthermore, the fibrous components also can improve the mechanical properties of the concrete matrix, such as its tensile strength and toughness, thereby further enhancing the bonding within the matrix. In addition, textile fibers can improve the toughness and ductility of concrete structures. When cracks begin to form, the fibers absorb energy through various mechanisms, such as fiber pull-out, fiber debonding, and fiber bridging, thus slowing crack propagation through the specimen. Fiber pull-out refers to the mechanism where an individual fiber is partially or completely pulled out from the surrounding concrete matrix during a load or stress application. This phenomenon generally occurs when the fiber is not strongly bonded to the matrix, and the applied load causes the fiber to disengage from the surrounding concrete. Fiber debonding, on the other hand, occurs when the bond between the fiber and the concrete matrix is completely broken, resulting in the separation of the fiber from the surrounding matrix. Fiber bridging is a beneficial mechanism that occurs when fibers span across a crack or void in the concrete matrix. When a crack forms under an applied load, the fibers present in the vicinity of the crack can bridge the gap, transferring stresses across the crack, thus resisting crack propagation. This bridging effect also helps to distribute the applied load and prevents further crack widening, leading to an improvement in the overall toughness and ductility of the concrete. Furthermore, textile fibers can help to control shrinkage by providing internal restraint and close packing. Fibers can also resist the tensile stresses caused by shrinkage, thus reducing the risk of cracking, thereby enhancing the overall durability of the concrete. Figure 3 shows the mechanisms of fiber pull-out, fiber debonding, and fiber bridging. Le Chen et al. extensively studied the effect of fiber orientation on the pull-out mechanism and the resulting mechanical strength of the concrete [99]. They observed that the fiber orientation and angle influenced the bond strength, and, hence, the flexural strength of the concrete. Wenchen Shan et al. [100] investigated the bond–slip behavior and damage characteristics of deformed rebar embedded in hybrid fiber-reinforced engineered cementitious composites (ECC) using the acoustic emission (AE) technique. They conducted a series of pull-out tests on 48 prism samples with variable rebar diameters (14 mm, 20 mm, and 25 mm), embedded lengths (3d, 4d, and 5d), and cover thicknesses (2.5d, 4d, 5d, and 6d). The bond–slip behavior of the ECC rebar presented a more ductile performance than conventional concrete (CC) rebar because of the fiber bridging effect. The bond stress of the ECC rebar could remain relatively stable, which can be attributed to the incorporated fibers providing inner reinforcement and redistributing the concentrated stress.

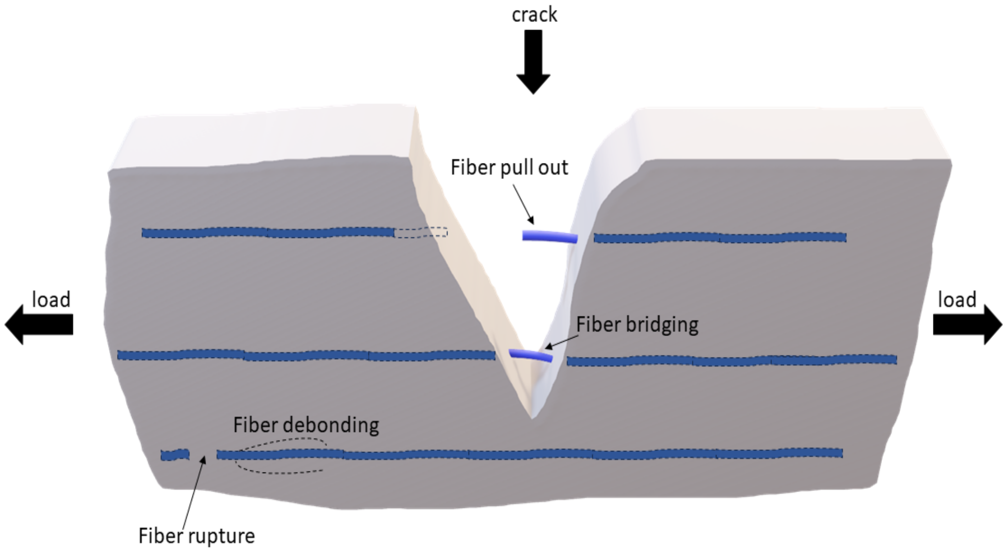

Figure 3. A schematic diagram of the mechanism of fiber pull-out, fiber debonding, and fiber bridging.

4.4. Thermal Resistance and Spalling

Spalling refers to the chipping, flaking, or breaking of the surface layer of concrete or other materials [101]. It typically occurs when the surface of the material deteriorates and separates from the underlying layers, resulting in the flaking of small pieces of the material. Generally, spalling occurs when concrete undergoes surface cracking and flaking, owing to exposure to a high temperature, such as in a fire scenario. In the case of a concrete structure, spalling can also happen due to various other factors, including freeze–thaw cycles, chemical attacks, reinforcement corrosion, structural overload, or due to physical impact. It is to be noted here that, when water infiltrates the pores of concrete and subsequently undergoes freezing, it expands. This expansion can exert pressure on the concrete structure and result in cracking and spalling in due course. Exposure to certain chemicals, such as de-icing salts, acid rain, or aggressive substances, can also cause the deterioration of the concrete surface. The chemical reactions or erosion caused by these substances tend to weaken the concrete and, thus, can lead to spalling. If the reinforcing element, steel, within the concrete starts to corrode, the resulting rust occupies a greater volume than the steel, resulting in the surrounding concrete cracking and spalling. This commonly occurs in structures where the steel reinforcement has been exposed to moisture or chloride ions. Excessive loads or impact forces on the concrete surface can also cause localized stress and lead to spalling, particularly if the concrete is not adequately designed or reinforced to handle such loads. Spalling is a significant concern, as it often compromises the structural integrity and durability of concrete structures. It can also result in the exposure of underlying layers, thus leading to further damage, and can lead to additional problems if not addressed properly. The addition of fibers to concrete can have a positive effect on the thermal resistance and spalling behaviour of the material, particularly in situations involving high temperatures or fire exposure. Fibers act as a thermal barrier by reducing the heat transfer within the material. They help to obstruct the movement of heat through the concrete matrix by creating a network of thermal bridges, which leads to improved insulation properties. As a result, the addition of fibers can help to reduce the rate of heat transfer and improve the overall thermal performance of concrete structures. It can also enhance the spalling resistance of the concrete by providing reinforcement and limiting crack propagation. Fibers help to bridge cracks that may form due to thermal expansion, thereby reducing the risk of spalling. The reinforcement effect of fibers helps to maintain the integrity of the concrete, preventing the rapid development of surface cracks and the subsequent spalling of the material. Furthermore, certain types of fibers, such as polypropylene or steel fibers, can undergo phase changes or melting during fire exposure.

Steel fibers have a melting point of ~1500 °C, while polypropylene fibers melt at lower temperatures of around 165 °C. In typical building fires, temperatures can range from 530–1093 °C or higher. According to their melting temperature, these fibers create voids or channels within the concrete matrix, allowing for the release of steam or gas generated due to the high temperatures. This release of pressure helps to minimize the build-up of internal stresses and reduces the likelihood of spalling. A schematic diagram representing the spalling prevention mechanism in fiber-reinforced concrete is shown in Figure 4.

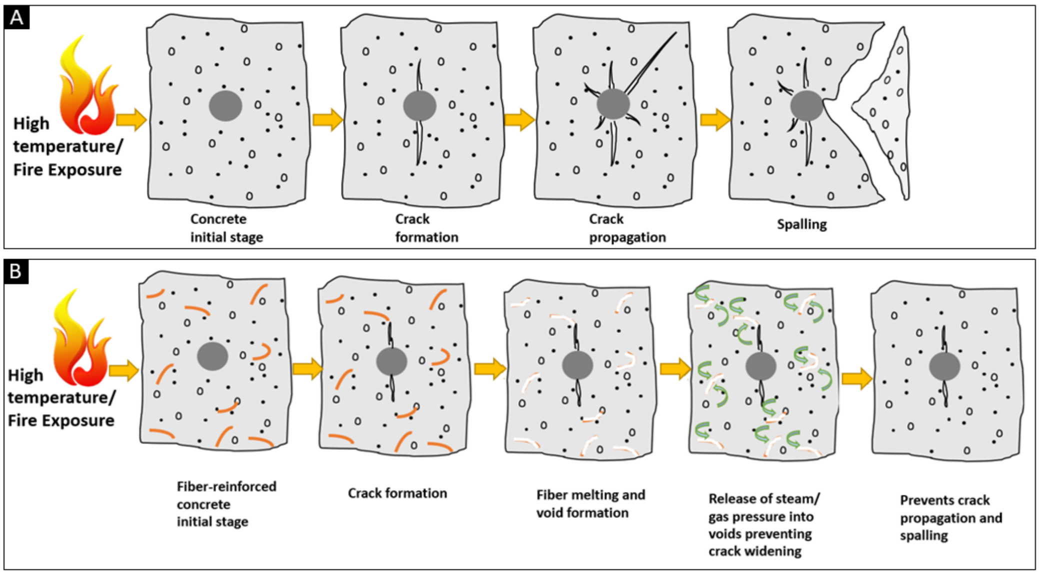

Figure 4. A schematic diagram of spalling behaviour in concrete without fibers (**A**) and with fibers (**B**).

In their study [102], Anand et al. investigated the impact of fibers on the engineering properties of concrete under elevated temperatures. Their findings revealed that the inclusion of both steel and polypropylene fibers led to an improved thermal resistance of the concrete. They observed a marginal reduction in spalling when an optimal dosage of fibers was added to the concrete mix. Another group of researchers investigated the dynamic evolution characteristics of the microstructural deterioration of unsaturated polyester resin-modified concrete for a bridge deck paving layer in a salt freeze–thaw environment [103], and found that the incorporation of unsaturated polyester resin in the concrete could restrain the germination, propagation, and nucleation of interior micro defects, diminish the morphologic irregularities of crack structures, exert a replenishing and refinement effect on the internal micropores, and delay the expansion at the interfacial transition zone. Dong Zhang and Kang Hai Tan [104] delved into the impacts of different polymer fibers on mitigating spalling in ultra-high-performance concrete (UHPC) under high temperatures. Their investigation encompassed a range of commonly used polymer fibers, including linear low-density polyethylene, ultra-high-molecular-weight polyethylene, polypropylene, polyamide, and polyester fibers. Through spalling tests, permeability measurements, and microscopic characterizations, they explored the behavior of these fibers in the spalling mitigation of UHPC. Their findings revealed that low-density polyethylene, polypropylene, and polyamide were effective in preventing concrete spalling, whereas ultra-high-molecular-weight polyethylene and polyethylene fibers did not offer the same level of spalling prevention. They attributed this to the high coefficient of thermal expansion of the polymer fibers, which contributed to an increased permeability in the concrete. The thermal expansion of polymer fibers led to the formation of microcracks even before fiber melting, influencing the pore size distribution and significantly enhancing permeability, thus improving the spalling resistance in fiber-reinforced concrete (FRC).

The study highlighted the importance of a high permeability below 200 °C for effective spalling resistance in FRC, occurring prior to fiber melting and contributing to a favorable spalling resistance. Additionally, low-density polyethylene, polypropylene, and polyamide showed an increase in permeability with temperature, albeit only slightly higher than that of FRC. The thermal expansion of these polymer fibers was crucial for spalling prevention, creating radial microcracks around the fibers and increasing permeability before fiber melting. The incorporation of polymer fibers primarily impacted the distribution of pores in the 0.1 to 10 µm range, corresponding to microcrack formation due to thermal expansion. Upon fiber melting, larger pores exceeding 10 µm appeared in the samples, indicating the formation of empty channels.

4.5. Density

The addition of fibers can affect the density of concrete [105]. Generally, the incorporation of fibers into concrete can lead to variations in its density, depending on the type of fiber. The addition of high-density fibers, such as steel or glass fibers, usually results in an overall increase in the density of the matrix. On the other hand, the addition of certain types of relatively lighter fibers, such as polypropylene or natural fibers, can contribute to the lightweight characteristics of concrete. Lightweight fibers can help in achieving lighter concrete structures, which can be beneficial for applications where weight reduction is desirable, such as in precast elements or structures with weight limitations. Alejandro Flores Nicolás et al. [106] investigated the effect of high-density recycled polyethylene fiber on the mechanical properties of FRC. They found that the recycled fibers showed a decrease in tensile strength and toughness, but a slight 2.3% increase in concrete flexural strength. Szymon Grzesiak et al. [107] investigated the influence of fiber addition on the properties of high-performance concrete and found that the FRC was strongly affected by the density of the used fiber and the presence of air voids. This effect can be attributable to the fiber dosage in the concrete mix. An increase in fiber dosage leads to a more closely packed system, which, therefore, increases the compressive strength. Sekhar Das et al. [108] evaluated the performance of polypropylene-fiber-reinforced recycled aggregate concrete. They concluded that, with an increase in the fiber content in the concrete, the density decreased. The reason for this decrease was the much lower specific gravity of the polypropylene fibers as compared to the concrete mixture. Fibers play an important role in determining the split tensile and flexural strength of FRC. The maximum increments for the FRC were 12.01% and 17.15% for the split and flexural strength values, respectively, over unreinforced concrete. The optimum value of the fiber content was 0.5% for the maximum strength.

4.6. Workability

The incorporation of textile fibers in concrete can influence its workability [109]. Generally, textile fibers tend to reduce the initial workability of concrete. Typically, the presence of fibers in the mix increases its viscosity and resistance to flow. This can also make the freshly formed concrete mixture stiffer and more difficult to handle. As a result, additional efforts may be required during mixing and placement to achieve the desired degree of workability. Incorporating textile fibers into the concrete mix can also affect the homogeneity and uniform distribution of other ingredients. Fibers often tend to intertwine and clump together, making it harder to disperse them evenly throughout the mixture. Proper mixing techniques, such as using suitable mixers and extended mixing times, can help to achieve a better fiber dispersion and improve workability. Textile fibers, especially longer fibers, tend to segregate from the mortar matrix during handling and transportation. This can lead to a non-uniform distribution of fibers, resulting in areas with a higher fiber concentration and others with lower or no fibers. Ensuring that fibers are added gradually during mixing and avoiding rapid changes in mixing speed can also contribute to a better dispersion. Generally, segregation can negatively impact the workability of the concrete and also compromise the intended reinforcement effect of the fibers. However, adequate mixing, careful handling, and proper vibration or compaction techniques can help to minimize segregation. The use of high-shear mixers or paddle mixers can improve the distribution of fibers within the concrete mix. Pre-treating fibers before adding them to the concrete mix, such as surface coating, chemical treatment, and heat treatment using surfactants or polymers, can reduce fiber agglomeration and improve their adhesion to the cement paste. Chemical treatment and heat treatment can modify fiber surfaces to enhance their compatibility with the concrete matrix. Optimizing the fiber geometry based on the specific application and concrete mix design or controlling the length and aspect ratio of the fibers can also lead to improved dispersion and mechanical properties. The use of superplasticizers in concrete mixes can also improve the compressive and flexural strengths, as well as resistance to abrasion, chemical attacks, and freeze–thaw cycles. By adjusting the dosage and type of superplasticizer, the setting characteristics of the concrete can be tailored to suit specific project requirements, such as an extended workability time or rapid setting for time-sensitive applications. Textile fibers can also accelerate the slump loss of concrete. Slump loss generally refers to a decrease in the workability of the mix over time due to factors, such as evaporation and hydration. Furthermore, the presence of fibers can increase the water demand and accelerate the setting time, thus leading to a faster slump loss. It is also important to account for this accelerated slump loss and, hence, adjust the mix design accordingly to maintain the desired workability during placement. Ketan Sonar and Sandeep Sathe highlighted, in their research, that incorporating fibers into concrete can lead to a reduction in its workability [110]. The presence of fibers hampers the flow of fresh concrete, resulting in a decreased workability. In a related study by Y. Mohammadi et al. [111], which focused on the properties of steel fibrous concrete containing mixed fibers in both fresh and hardened states, they determined that a fiber combination of 65% 50 mm fibers and 35% 25 mm long fibers was the most suitable for achieving a high compressive strength, split tensile strength, and flexural strength in fiber-reinforced concrete (FRC). However, they noted that a better workability was achieved as the proportion of shorter fibers increased in the concrete mix.

4.7. Shrinkage and Creep Reduction

Fibers, particularly synthetic fibers like polypropylene or steel fibers, can help to reduce the plastic shrinkage and drying shrinkage in concrete. By bridging microcracks and restraining crack propagation, fibers limit the extent of shrinkage-induced cracking, which can lead to an improved overall dimensional stability and reduced shrinkage-related issues. The presence of fibers alters the stress distribution within the concrete matrix, providing internal reinforcement that counteracts the tensile stresses generated during drying and plastic shrinkage. This reinforcement mechanism helps to mitigate shrinkage-induced cracking, which is beneficial for the long-term durability and aesthetics of concrete structures. Fiber reinforcement can contribute to reducing creep or time-dependent deformation in concrete. Fibers act as load-bearing elements that distribute applied loads more evenly throughout the matrix, reducing localized stress concentrations and potential creep effects. This can result in an improved structural performance over time, particularly in applications with sustained loads or long-term service conditions. By limiting creep and minimizing deformation under sustained loads, fiber-reinforced concrete can maintain its dimensional stability, structural integrity, and serviceability over extended periods. This enhanced durability against time-dependent deformations is especially beneficial for structures subject to variable loading or environmental conditions [93].

4.8. Durability against Freeze–Thaw Cycles

Fibers, especially microfibers or macrofibers with high aspect ratios, can create a network that helps to protect concrete from damage caused by freeze-thaw cycles. The fibers act as barriers that inhibit the ingress of water and harmful agents into the concrete matrix, reducing the risk of freeze–thaw damage, scaling, and surface deterioration. This helps to prevent the propagation of freeze–thaw-induced cracks, preserving the structural integrity and long-term durability of concrete elements exposed to harsh environmental conditions [112].

4.9. Corrosion Resistance

Certain types of fibers, such as steel fibers with appropriate surface coatings or corrosion inhibitors, can help to inhibit corrosion in concrete exposed to aggressive environments. These fibers act as sacrificial anodes or provide a protective barrier that reduces the penetration of chloride ions and other corrosive agents, extending the service life of reinforced concrete structures. By enhancing corrosion resistance, fiber-reinforced concrete can withstand exposure to marine environments, deicing salts, chemical attacks, and other corrosive agents more effectively than conventional concrete. This contributes to the long-term durability, structural performance, and maintenance-free lifespan of concrete structures in challenging conditions [113].

A detailed inference list relating to studies based on polymer-fiber-incorporated concrete is listed in Table 2.

Table 2. Studies based on polymer fiber-incorporated concrete.

Polymer Fiber Used	Improved Property of Concrete	Inference	Ref. No.
Nylon, polypropylene	Thermal stability	The combination of NY and PP fibers showed a synergistic effect on spalling prevention. That is, the combination of NY and PP fibers provided better protection from spalling with a lower fiber demand than that of the addition of PP fiber alone.	[114]
Polyester	Mechanical strength and acoustic properties	Increase in flexural breaking stress for the plaster with polyester fibers. The sound absorption coefficient and the sound insulation performance of the plaster with fibers showed good values for building applications. When compared to the plaster without fibers, thermal conductivity was reduced by about 29%, mechanical resistance was increased by about 76%, and absorption coefficient was reduced by about 48%.	[115]
Polyester	Mechanical strength	Optimum concrete mix with fiber-micronized silica enhanced compressive, split–tensile, and flexural strength.	[116]
Polypropylene	Mechanical strength	The addition of polypropylene fiber to the concrete increased the compressive strength of the concrete by 6.15%.	[117]
Nylon	Crack control	The incorporation of fibers into concrete could increase the roughness of the crack surface and extend the seepage path to a certain extent, which narrowed the effective water passage and reduced the crack permeability.	[93]
Poly-acrylonitrile-based carbon fibers	Bond strength	The shear–bond strength of CF was improved by 37.9%.	[118]
Polyester	Durability under salt water	Unsaturated polyester resin incorporation would impose a visible delay effect on the deterioration and expansion of the interfacial transition zone structure irrespective of freeze–thaw salt water or fresh water.	[112]

Table 2. *Cont.*

Polymer Fiber Used	Improved Property of Concrete	Inference	Ref. No.
Polyester, polypropylene	Durability under alkaline environment	In general, concrete samples that were reinforced with PET and PP fibers exhibited a higher crack resistance and crack propagation in comparison to reference concrete. Results are indicative of the significant effect of added fibers on the compressive and tensile splitting strength of reinforced concretes.	[119]
Nylon	Crack control	The fibers incorporated into concrete mainly reduced the crack permeability by increasing the roughness of the crack surface.	[93]
Polyester	Mechanical strength	Polyester fibers, gamma rays, and post-cure process were satisfactory ways to develop polymer concretes with higher values of deformation and strength, which guarantees a more ductile material.	[120]
Polyester, steel fibers.	Mechanical strength	Compressive strength saw a 17% improvement. Toughness was also improved compared to the control samples.	[121]
Polyester	Mechanical strength and resistance to UV radiation, acids, alkalis, water, and saline solution	Fiber reinforcement of polymer concrete significantly improved modulus of rupture by about 20% and fracture toughness by about 55%.	[122]
Polypropylene	Mechanical strength	Flexural strength and toughness increased by approximately 19% and 143%, respectively, with the use of hybrid yarn. The thermoplastic material (polypropylene) on the hybrid yarn increased the strength of the structure by protecting the reinforcement materials.	[123]
Polyester	Fracture resistance, freeze–thaw damage	Adding 0.25% polyester and 6% calcium lignosulfonate to asphalt concrete increased the fracture resistance and improved the brittleness.	[124]
Polypropylene, nylon	Mechanical strength	Multi-filament polypropylene fibers had a positive effect on the tensile strength, as both flexural and splitting tensile strengths were up to 86% higher than the control concrete.	[125]
Nylon	Mechanical strength, crack control	The incorporation of recycled nylon fiber increased the crack resistance of concrete after cracking in the plain concrete matrix. In total, 0.25–0.5% recycled nylon fiber can be considered for optimum mechanical performance. Water absorption and chloride penetration depth of fiber-reinforced concrete were reduced by 11.5% and 29.2%, respectively, with respect to control mix.	[113]
Nylon	Mechanical strength	Concrete with 0.25 percent nylon fiber added concrete had a compressive strength 16.8% greater than ordinary concrete.	[126]
Nylon	Mechanical strength, crack control	The compressive and splitting tensile strengths and modulus of rupture (MOR) of the nylon fiber concrete improved by 6.3%, 6.7%, and 4.3%, respectively, over those of the polypropylene fiber concrete.	[127]

Table 2. *Cont.*

Polymer Fiber Used	Improved Property of Concrete	Inference	Ref. No.
Nylon	Mechanical strength	Under a sulfuric acid environment, an increase in the nylon granule amount in steel fiber-reinforced concrete caused a rise in its compressive capacity.	[128]
Nylon, glass fiber	Crack control	Glass and nylon fibers in concrete reduced early-stage micro cracking in bridge decks. The compressive, splitting–tensile, and flexural toughness indices of GFRC were increased by 4.7%, 17%, and 23%, respectively, compared to control. Those of NFRC are also increased by 2.7%, 16%, and 21%, respectively, compared to that of plain concrete.	[129]

5. Challenges in the Use of Recycled Fibers in Concrete

5.1. Quality and Consistency

Generally, the incorporation of recycled fibers in concrete offers several environmental and sustainability benefits. However, there are also certain challenges associated with the use of recycled fibers in concrete. One of the primary challenges of using recycled fibers in concrete is ensuring their quality and consistency. Recycled fibers are often derived from various sources, such as post-consumer waste or industrial by-products, which can result in variations in fiber properties. Factors such as fiber length, aspect ratio, surface characteristics, and residual contaminants may vary, thus affecting the performance and behaviour of the fibers in concrete [119,130]. Recycled fibers may exhibit variability in their tensile strength, modulus of elasticity, and aspect ratio due to factors such as the fiber source, processing methods, and impurities. This variability can lead to inconsistent reinforcement effects in concrete, affecting the structural integrity and load-bearing capacity of concrete elements over time. Therefore, ensuring a consistent fiber quality and adhering to appropriate quality control measures are essential. Implementing control measures for recycled fibers, including standardized testing protocols to assess mechanical properties, fiber dimensions, and chemical composition and ensuring that recycled fibers meet these criteria before their incorporation into concrete mixes, can solve this problem to an extent. Compatibility tests like pull-out tests, fiber push-through, and monitoring crack propagation, deformation behavior, and post-crack performance in fiber-reinforced concrete specimens to assess their long-term durability are essential to ensuring the quality of the fiber. For recycled fiber, lifecycle assessments (LCAs) and environmental impact assessments (EIAs) to evaluate their environmental footprint are in the infancy stage.

Recycled fibers may contain contaminants or residual materials from their original sources, such as adhesives, coatings, dyes, or other substances. These contaminants can negatively impact the bond strength between the fibers and the concrete matrix, or interfere with the hydration process of cementitious materials. Contaminants may also contribute to degradation or durability issues in the concrete over time. The processing methods used for recycling fibers can also vary, leading to inconsistencies in the physical and mechanical properties of the resulting fibers. In addition, factors such as fiber cleaning, sorting, and processing techniques can influence the fiber quality and performance.

Variability in fiber dispersion, distribution, and homogeneity within concrete mixes can result in localized fiber clustering, voids, or weak zones. A poor fiber dispersion can lead to non-uniform reinforcement, reduced ductility, and potential stress concentration points, compromising the overall durability of concrete structures. Furthermore, inadequate or inconsistent processing method(s) may result in fibers with sub-optimal properties or residual contaminants. Currently, there is also a lack of standardized protocols and specifications for recycled fibers used in concrete. The absence of clear guidelines and quality standards makes it even more challenging to assess the suitability and performance of different types of recycled fibers. This lack of standardization can also hinder the widespread adoption and use of recycled fibers in concrete applications. The availability of consistent and high-quality recycled fibers may be limited based on regional recycling infrastructure and the availability of suitable waste sources. The establishment of a reliable and sustainable supply chain for recycled fibers can be challenging, especially in areas where recycling practices are less developed or where specific types of waste materials are scarce. Only a few recent studies have been reported explaining the gradation and classification of recycled fiber, which can open the door to an easier availability of recycled fiber for various applications [131].

Rocco Furferi and Michaela Servi [132] developed a straightforward yet efficient machine vision algorithm for the color classification of recycled wool fabrics. Their approach involved using a probabilistic neural network to accurately classify plain, colored, and regenerated wool fabrics based on color. The system relied on defining a set of color classes for classification and utilized a specially designed acquisition system to capture images of the fabrics. Image-processing algorithms were then applied to extract the relevant color information from the acquired images. This data were used to train the neural network algorithms, enabling them to categorize fabric samples according to their color properties. When tested using a dataset of fabrics, the system achieved an impressive reliability index of around 83%, showcasing its effectiveness compared to other color classification methods commonly used in the textile and industrial sectors.

5.2. Fiber Compatibility and Bond Strength

Recycled fibers may exhibit different compatibility and bonding characteristics with the concrete matrix compared to conventional fibers. The presence of contaminants or surface coatings on recycled fibers can affect their interaction with the cementitious matrix, potentially leading to a reduced bond strength or inadequate dispersion. Achieving a strong bond between recycled fibers and the matrix is crucial for an optimal performance, and proper surface treatment or modification techniques may be required to enhance compatibility. It should be noted here that different types of fibers, such as steel, polypropylene, glass, or carbon fibers, have varying mechanical properties and surface characteristics. Achieving a strong bond between fibers and the matrix requires ensuring the proper adhesion and load transfer between them. Furthermore, the proper dispersion and distribution of fibers within the concrete matrix are essential for achieving uniform reinforcement and the optimal bond strength. An inadequate fiber dispersion can often lead to clustering or agglomeration, resulting in localized areas of a higher fiber concentration and weaker bonding. Jawad Ahmad and Zhiguang Zhou explained this in their article [133]. The alignment and orientation of fibers within the concrete matrix can influence their bond strength. In some cases, fibers may align parallel to the casting direction, or settle at the bottom of the formwork during concrete placement. This uneven distribution or preferential orientation can often result in a reduced bond strength in certain directions and a compromised overall performance.

Certain types of fibers, especially those with smooth surfaces or low surface energy, may have a limited bond strength with the cementitious matrix. Surface treatment or modification techniques, such as chemical treatments or coatings, can be employed to enhance the fiber–matrix interaction and improve the bond strength [112]. However, finding the most effective treatment method for specific fiber types and ensuring their long-term durability can be sometimes challenging. Some fibers may also be susceptible to moisture absorption or degradation over time, which can weaken the bond between the fibers and the matrix. Moisture-sensitive fibers, such as natural fibers or certain synthetic fibers, may experience dimensional changes or a loss of mechanical properties when exposed to moisture, compromising the bond strength and overall performance of the concrete.

5.3. Fiber Gradation and Distribution

Meng, Z et al. explained, in their article, some observations from their experiment regarding the fiber factor for the fresh and hardened properties of polyethylene-fiber-reinforced geopolymer mortar [134]. The gradation and distribution of recycled fibers within the concrete matrix can pose challenges. Irregular fiber shapes and varying fiber lengths in recycled fibers can also affect their dispersion and distribution, leading to non-uniform fiber reinforcement. This non-uniform distribution may result in inconsistent mechanical properties and a reduced performance in terms of crack control, strength, or durability. Effective mixing techniques and proper fiber dosing strategies are often necessary to ensure a homogeneous distribution of recycled fibers in the concrete. Fibers, especially those with high aspect ratios or entangled structures, tend to cluster or agglomerate within the concrete mix. The aspect ratio is the ratio of the length of the fiber to its diameter. Due to their inherent characteristics, fibers can be difficult to uniformly disperse within a mix. Factors such as mixing methods, mixing time, and the rheological properties of the mix can also influence the extent of fiber distribution. An inadequate mix homogeneity can generally result in inconsistent reinforcement and a compromised performance. During the casting and compaction process, some fibers may settle at the bottom of the formwork or migrate due to gravitational forces. This settling can lead to a non-uniform distribution of fibers, with higher concentrations near the bottom of the structure [135]. As a result, the upper portions of the concrete may have insufficient fiber reinforcement, affecting the overall strength and performance.

Furthermore, fibers, especially longer ones, can segregate or separate from the concrete matrix during placement, especially if the mix has a high water-to-cement ratio, or owing to excessive vibration. This segregation can lead to a non-uniform fiber distribution and compromised reinforcement in certain regions of the structure. Fiber entanglement can impede their separation and dispersion, resulting in an uneven fiber distribution and reduced effectiveness in crack control and reinforcement. Employing appropriate mixing techniques, such as high-shear mixers or lengths that are compatible with the specific application, can facilitate a better dispersion and distribution. Employing suitable admixtures or chemical additives can also improve fiber dispersion and prevent fiber clustering. Adopting proper casting and compaction techniques is another way to minimize fiber settling and segregation.

5.4. The Chemical Resistance and Durability of Fibrous Materials

Research is progressing on the chemical resistance and durability of fibrous materials in FRC. A few articles have been reported that explain some critical observations based on this as follows. The durability of concrete is a critical aspect, and the incorporation of recycled fibers can present durability challenges to concrete structures. The chemical resistance and durability of fibers used in concrete can also pose problems in terms of their performance and long-term behaviours. Furthermore, recycled fibers may be susceptible to chemical attacks, moisture absorption, or degradation over time, which can negatively impact the long-term durability of the concrete elements [136]. In addition, concrete structures are sometimes exposed to various chemical environments, such as acidic or alkaline solutions, chlorides, and other aggressive substances. The chemical resistance of fibers is crucial to ensuring their long-term performance in such environments. Some fibers may be susceptible to chemical attacks, which often leads to fiber degradation, a loss of mechanical properties, or a reduced bond strength within the concrete matrix [137]. Another problem termed the Alkali–Silica Reaction (ASR) is a chemical reaction that can occur between certain reactive forms of silica present in aggregates and the alkaline environment of concrete. In the presence of moisture, this reaction can cause expansion, cracking, and ultimately, a decrease in the durability of the concrete. Some types of fibers, particularly those with a high silica content, such as glass fiber, may be susceptible to the ASR, and their presence in a concrete mix could potentially exacerbate this reaction.

Fibers, especially those made from organic or natural materials, may also have hygroscopic properties, meaning they are capable of absorbing and releasing moisture [138]. Excessive moisture absorption can lead to dimensional changes, weakening of the fibers, and potential debonding from the concrete matrix. Furthermore, cycles of moisture absorption and desorption can cause stress within the concrete, leading to cracking and a reduced durability. In addition, concrete structures exposed to freeze–thaw cycles or wet–dry conditions require good durability characteristics. Fibers that are susceptible to freeze–thaw damage or moisture-induced degradation may exhibit a reduced performance and can contribute to the deterioration of the concrete matrix. Therefore, ensuring that the fibers used in such environments have a sufficient durability and resistance to these cycles is essential. Over time, the performance of recycled fibers can be also influenced by factors such as aging, exposure to UV radiation, and temperature variations.

Furthermore, fibers may undergo degradation, a loss of mechanical properties, or changes in their chemical composition, and these can, in turn, influence their overall durability and effectiveness in reinforcing the concrete matrix. Hence, understanding the long-term behaviour and performance of fibers is crucial for predicting their durability in concrete structures [139] Ideally, the selection of fibers should duly consider their chemical resistance and durability properties for specific exposure conditions. Sometimes, it is desirable to employ an appropriate surface treatment or modification of fibers in order to enhance their resistance to chemical attacks or improve their compatibility with the concrete matrix. In addition, the optimization of the concrete mix design, including the selection of appropriate admixtures and protective measures, is a key factor for enhancing the overall durability of the concrete. Furthermore, the testing and evaluation of fiber performance under relevant exposure conditions are essential. These include tests to evaluate their chemical resistance, durability in freeze–thaw cycles, and to gauge accelerated aging. In addition, the regular inspection, maintenance, and monitoring of concrete structures containing fibers are crucial to identify any signs of degradation or long-term durability issues. A careful evaluation of the compatibility of recycled fibers with the specific exposure conditions, as well as appropriate measures to address potential durability concerns, is necessary to ensure the longevity of the concrete structures in question.

5.5. Availability of Recycled Fiber

Along with technical challenges, availability and cost affirmation also hinder the growth of the recycling industry. Most recycling methods are not commercially viable due to their high dependence on energy consumption. Recently, some companies have established good practices of recycling carbon fiber waste by recycling up to 100%. They could produce recycled carbon fiber costs around USD 18–25 per kg, whereas virgin carbon fiber is valued at USD 33–66 per kg. The production of virgin carbon fiber is expensive but also energy-intensive (energetic cost is 183–286 MJ/kg). Recycled fiber could decrease costs by 70% and energy costs by almost 98%. Even though recycled fiber can reduce the cost significantly, the availability of recycled fibers can be a challenge The collection, sorting, and processing of recycled fibers require additional resources and may increase the overall cost of production compared to conventional fibers. Sources of recycled fibers may also be limited based on regional recycling facilities and access to suitable waste sources. Therefore, the economic feasibility and scalability of using recycled fibers in concrete need to be carefully considered. Furthermore, the coordination of the procurement, transportation, and delivery of fibers to batching plants or construction sites can be challenging, particularly for projects located in remote areas or regions with inadequate infrastructure. The additional costs associated with logistics and transportation can further reduce the overall cost-effectiveness of using fibers in concrete. The lack of standardized protocols and certification systems for fibers used in concrete can also affect their availability and cost. Without an established certification processes, it can be difficult for suppliers and contractors to ensure the quality and consistency of the fibers, leading to uncertainties in their material performance and suitability. Other sustainable concrete materials have successfully developed standards, providing valuable insights into the standardization process. For example, ASTM C618/C618M [140] provides specifications for fly ash as a mineral admixture in concrete, covering physical and chemical properties, performance criteria, and quality control measures. This standard has facilitated the use of fly ash in concrete mixes, demonstrating the feasibility of its standardization for sustainable materials. ASTM C989/C989M [141] outlines specifications for ground granulated blast-furnace slag (GGBFS) as a supplementary cementitious material in concrete, addressing composition, fineness, strength activity index, and durability requirements. This standard has supported the adoption of slag cement in sustainable concrete applications. ASTM C33/C33M provides specifications for concrete aggregates, including recycled aggregates, covering grading, quality, and performance criteria [142]. This standard demonstrates the importance of material specifications in ensuring the quality and consistency of sustainable concrete mixes. The development of standardized testing methods and specifications for recycled fiber is essential to address industry demands, regulatory requirements, and sustainability goals. These standards should encompass testing protocols for mechanical properties, durability performance, fiber–matrix compatibility, quality control measures, and guidelines for material sourcing and processing [143–146].

6. Effects of Additive Materials/Admixtures on Textile-Fiber-Reinforced Concrete (TFRC)

In addition to textile fibers, some concrete mixtures may also include additive materials like aluminum oxide, gypsum, zinc oxide, and pozzolan-like material, such as metakaolin. Generally, these additives can further enhance the properties of concrete in different ways.

6.1. Pozzolanic Materials

Metakaolin is a calcined form of kaolin clay with a high pozzolanic reactivity [147], meaning it reacts with the calcium hydroxide present in the cement paste to form additional calcium silicate hydrates (C-S-H). The formation of more C-S-H gel often leads to improved bonding and a denser microstructure, thus resulting in a higher compressive strength of the TFRC. Metakaolin also reduces the porosity of the cementitious matrix, hence making concrete that is less permeable to moisture and aggressive chemicals. Thus, these materials are more resistant to chemical and sulfate attacks, and other types of environmental degradation. As mentioned earlier, the Alkali–Silica reaction (ASR) can be a potential durability issue in concrete, where reactive silica in aggregates reacts with the alkalis in cement, leading to expansive gel formation and cracking. The addition of metakaolin can also help to mitigate ASR, improving the long-term durability of the TFRC. Furthermore, the incorporation of metakaolin in the concrete mix can enhance its workability. Generally, it acts as a pozzolanic material and provides a ‘lubricating’ effect, reducing the water demand of the mixture while maintaining a good flow and ease of placement during construction. Metakaolin reacts with calcium hydroxide in the presence of water to form additional cementitious compounds such as calcium silicate hydrate gel. This pozzolanic reaction consumes excess water in the mix, reducing the water-to-cement ratio and improving the overall workability without compromising strength or durability. The reduced water demand contributes to a more cohesive and manageable concrete mixture.

Like alumina, metakaolin can help to control drying shrinkage in TFRC. By reacting with calcium hydroxide and forming additional C-S-H, it can contribute to the formation of a more stable cementitious matrix, thus resulting in a reduced drying shrinkage coupled with a lower potential for cracking. The improved microstructure and bonding within the concrete, facilitated by metakaolin, can also result in an increase in flexural strength. In addition, the use of metakaolin as an additive in TFRC reduces the reliance on cement, which is a significant contributor to CO_2 emissions during its production. Thus, incorporating metakaolin can lead to more sustainable and environmentally friendly concrete mixtures. Metakaolin can also improve the appearance and color of concrete elements. Its fine particle size and white color can generally contribute to a smoother and lighter surface finish, which may be desirable for certain architectural and decorative applications.

Some natural materials, such as volcanic ash, calcined clay, and diatomaceous earth, exhibit pozzolanic properties [148]. Therefore, these materials can be used as supplementary cementitious materials to improve the performance of concrete. Fly ash is a by-product of coal-fired power plants and is a finely divided pozzolan that improves the workability, durability, and strength of concrete. It also reduces the heat of hydration and enhances sulphate resistance. Furthermore, fly ash has a lower heat of hydration compared to pure cement. Its inclusion in TFRC mixtures generally helps to reduce the heat generated during the cement hydration process, which is particularly beneficial in large concrete pours, or while designing massive structures. Silica Fume, also known as micro silica, is a highly reactive pozzolan produced during the production of silicon and ferrosilicon alloys. It can enhance the strength, [149] impermeability, and durability of concrete, thus making it suitable for high-performance applications [150]

6.2. Gypsum

The addition of gypsum to TFRC can have several effects on the properties and performance of the composite material [151]. Gypsum is generally used as a setting time regulator or delay material in concrete. By adding gypsum to the concrete mix, the initial setting time of the cementitious paste can be prolonged. This extended setting time allows for more workability and ease of handling during construction, especially in large-scale projects or in hot weather conditions. The presence of gypsum in TFRC can also improve the workability and cohesiveness of the fresh concrete. Furthermore, it can act by reducing the water demand while maintaining a proper flowability and consistency. This makes the concrete mixture easier to place, compact, and finish. Gypsum can also help to reduce the heat of hydration during the curing process of concrete structures. This is beneficial in large concrete pours or massive structures, as excessive heat generation can lead to thermal cracking. Furthermore, the controlled heat evolution helps in minimizing the risk of thermal-related issues.

Gypsum can also enhance the sulfate resistance of TFRC. It reacts with soluble calcium hydroxide, which is produced during cement hydration, to form calcium sulfate compounds, which can mitigate the detrimental effects of sulfate attack, especially in certain aggressive environments. Gypsum can also contribute to the overall durability of the TFRC by reducing permeability and improving resistance to chemical attacks. The presence of gypsum often leads to a denser cementitious matrix, reduces the ingress of harmful substances, and increases concrete's long-term performance. In addition, gypsum can help to mitigate the risk of the Alkali–Silica reaction (ASR) in concrete. Gypsum can react with alkalis and prevent their participation in the ASR. Gypsum is generally compatible with most types of textile fibers used in concrete reinforcement [152] Generally, its presence does not negatively affect the bonding between the fibers and the cement matrix.

6.3. Aluminum Oxide (Alumina)

The addition of alumina to textile-fiber-reinforced concrete (TFRC) can have several positive effects on the properties and performance of the composite material [153] Alumina is a ceramic material known for its high strength and hardness. When incorporated into TFRC, it generally acts as a reinforcement material, thus adding to the mechanical properties of the concrete. It is a relatively stable compound and is resistant to environmental degradation. When present in TFRC, it also helps to improve the concrete's resistance to chemical attacks, including the effects of acidic or alkaline substances. This improved durability also ensures that the concrete can withstand harsh environmental conditions, while maintaining its structural integrity over an extended period. In addition, alumina particles act as crack arresters, preventing cracks from propagating through the concrete and improving its overall crack resistance. Furthermore, alumina is bestowed with an excellent thermal stability, and hence can withstand higher temperatures [154]. In TFRC, this property contributes to the concrete's ability to resist thermal stresses, thus making it suitable for applications where temperature variations are significant, such as in fire-resistant structures.

The addition of alumina oxide can also help to mitigate drying shrinkage in the concrete. Furthermore, alumina particles can promote better bonding between the textile fibers and the cement matrix. The concentration of alumina in the TFRC mixture can also be adjusted to achieve specific engineering properties based on the requirements of the specific application(s). By varying the alumina content, designers can fine-tune the concrete's performance to suit different applications. The combination of textile fibers and alumina oxide can create a synergistic effect, mainly manifested through the enhancements in tensile and flexural strengths and an overall improvement in the toughness of the concrete structures. For the interaction between the admixture and fiber, the proper selection and dosage of admixtures are crucial to ensure a homogeneous mix that incorporates the fibers uniformly without causing unwanted segregation [155] Admixtures can also influence the dispersion of fibers in the concrete matrix. A good degree of fiber dispersion is crucial to achieving the desired mechanical properties and ensuring an effective check on crack control. Some admixtures can also aid in maintaining a uniform distribution of fibers, thus helping to improve the overall performance of the TFRC. Certain admixtures, such as polymer-based additives, can also enhance the bonding between fibers and the cementitious matrix. Admixtures, such as accelerators or delay materials, can influence the setting time of the concrete. When using fibers in TFRC, it is important to consider how these admixtures may affect the curing process, as they can influence the development of fiber–matrix bonds and the overall concrete strength. A properly selected admixture can help to mitigate segregation and bleeding [156] issues that might arise when using fibers in the concrete mix. Segregation can occur when heavier materials, like aggregates or fibers, settle to the bottom of the mix, while bleeding is the upward movement of water to the surface. The effective use of admixtures can help to control these issues and ensure a homogeneous mix. Admixtures can also aid in the retention of workability over an extended period. This is particularly important for large or complex construction projects where the time between mixing and placing is significant. To ensure a successful interaction between admixtures and fibers in TFRC, the thorough testing and optimization of the concrete mix are necessary. Table 3 summarizes the effect of different admixtures on FRC properties.

Table 3. Effect of different admixtures on FRC properties.

Admixture Type	Example	Effects on FRC Properties	Ref.
Superplasticizers	Polycarboxylate Ether (PCE), Sulfonated Melamine Formaldehyde (SMF), Sulfonated Naphthalene Formaldehyde (SNF), Polycarboxylic Acid (PCA), Modified Lignosulfonates, Nano Superplasticizers.	Improved workability and flowability, reduced water–cement ratio, enhanced dispersion and orientation of fibers within the matrix, reduced risk of fiber balling or clustering during mixing and placement	[157]
Accelerators	Calcium Chloride, Calcium Nitrate, Sodium Nitrite, Potassium Silicate, Hydrogen Peroxide.	Accelerated early strength gain, shortened curing time, enhanced bonding between fibers and matrix, improved resistance to high temperatures and early-age cracking	[158]
Retarders	Lignosulfonate-Based Inhibitors, Polycarboxylate Ether (PCE), Citric Acid-Based Inhibitors, Sodium Citrate-Based Inhibitors, Tartaric Acid-Based Inhibitors, Sugar-Based Inhibitors, Phosphonate-Based Inhibitors, Gypsum.	Delayed setting time, improved workability and placement consistency, reduced risk of cold joints and surface defects due to prolonged workability, enhanced hydration of cementitious materials.	[159]

Table 3. *Cont.*

Admixture Type	Example	Effects on FRC Properties	Ref.
Pozzolanic Materials	Fly Ash, Silica Fume, Metakaolin, Rice Husk Ash, Calcined Clays, Natural Pozzolans (volcanic ash, calcined clay, and diatomaceous earth), Blended Cement.	Increased compressive strength and durability, enhanced pore refinement, and microstructure, improved resistance to Alkali–Silica reaction (ASR) and sulfate attack, reduced permeability and chloride ion penetration	[160]

7. Effect of Fiber Size Reduction: Scope of Nanofibers in Fiber-Reinforced Concrete

Nanofibers have gained significant attention in recent years due to their unique properties and potential applications in various fields of electrochemical, medicinal, and environmental engineering, which also includes the production of fiber-reinforced concrete [RPC] [161]. The scope of nanofibers in fiber-reinforced concrete is promising and holds several potential benefits. Nanofibers, typically with diameters in the nanometer range, possess exceptional mechanical properties, including a high tensile strength and modulus [162]. Due to their small size, nanofibers also have a significantly higher aspect ratio compared to conventional fibers' aspect ratio. The relatively high aspect ratio of nanofibers essentially means that they are much longer and thinner compared to conventional fibers. Increasing the number of fibers in a unit volume can be achieved by decreasing the diameters of fibers and by facilitating the migration of the constituent particles of the fiber from the bulk to its surface. This elongated and slender shape gives nanofibers a much larger surface area relative to their volume. In fact, nanofibers can have surface areas that are several orders of magnitude greater than the same mass of macro-scale fibers. The increased surface area of nanofibers is attributed to their high aspect ratio, and this has several important implications. When the size of reinforcement fibers decreases, the surface area of the fibers in contact with the concrete matrix also increases. This increased surface area plays a crucial role in enhancing the degree of bonding between the fibers and the surrounding cement paste, thus leading to an improved load transfer and potentially higher strength of the fiber-reinforced concrete. As already mentioned, the bonding between the fibers and the cement paste is critical for the effective transfer of stresses from the matrix to the fibers. Nanofibers can, thus, facilitate a better dispersion and distribution of imposed stress forces within the matrix due to their increased surface area. This can also lead to an improved homogeneity and uniformity of the fiber-reinforced concrete, and it allows the fibers to effectively bridge cracks and distribute the applied loads, thereby enhancing the overall mechanical properties of the concrete.

Furthermore, the higher surface area of nanofibers also influences their interactions with the surrounding materials. In the case of cement-based composites, the larger surface area of nanofibers can, thus, provide more sites for chemical reactions to occur, such as the formation of hydration products or the bonding between fibers and the cement matrix. This can, in turn, contribute to the development of a stronger degree of interfacial bonding and improved mechanical properties. It is also important to note that the larger surface area of nanofibers does not necessarily translate directly into a higher strength or improved performance of the structures that they form a part of. For instance, the effectiveness of nanofibers in enhancing concrete properties depends on various factors, including their nature of dispersion, degree of interfacial bonding, and extent of compatibility with the matrix. It is to be noted here that achieving a uniform dispersion of nanofibers and ensuring their adequate bond with the cement paste are critical aspects for realizing the potential benefits of their increased surface area.

Incorporating nanofibers into concrete matrices can also significantly enhance the mechanical properties of FRC, such as tensile strength, flexural strength, and impact resistance. Due to their smaller dimension and high aspect ratio, nanofibers can effectively bridge microcracks and prevent their propagation, leading to an improved overall durability and crack resistance. The fine network of nanofibers can also obstruct the movement of water, chloride ions, and other deleterious substances, thereby improving the resistance to degradation mechanisms, such as corrosion and freeze–thaw damage. Compared to conventional macro or microfibers, nanofibers can achieve significant reinforcement effects at lower fiber contents. This reduction in fiber content can also lead to an improved workability and aesthetics of concrete while maintaining or enhancing its mechanical properties where some nanomaterials can act as water reducers or superplasticizers. Nanofiber fills the gaps between larger particles in the cementitious matrix, which leads to a better dispersion of cement particles, improved hydration kinetics, and a more homogeneous mixture, which improves the lubrication between particles, reducing friction and enhancing the flowability of the concrete mix resulting in enhanced workability.

Nanofibers can also serve as conductive fillers in FRC, thus enabling self-sensing capabilities. By monitoring the electrical properties of nanofiber-reinforced concrete, such as electrical resistance, it is possible to detect and monitor the development of cracks and structural health in real time. Nanofibers can be also functionalized to impart specific properties to FRC, such as electrical conductivity and anti-microbial properties.

A combination of nanofibers and microfibers can reduce the tendency of fiber balling or clustering during mixing and placement, resulting in a more homogeneous mix with a better dispersion of fibers, and can enhance crack resistance even more. Microfibers are effective in bridging larger cracks, while nanofibers fill in smaller cracks and pores, preventing crack propagation and increasing the energy absorption capacity of the concrete. Nanofibers reduce water evaporation and internal drying shrinkage, while microfibers provide reinforcement that restrains deformations over time, resulting in reduced long-term creep.

Wang et al. [163] introduced a novel material called carbon-nanofiber-reinforced reactive powder concrete (CNF-RPC), which amalgamates the advantageous characteristics of carbon nanofibers (CNFs) and reactive powder concrete (RPC). This advanced material possesses multifunctional attributes, making it highly adaptable for diverse engineering applications. Their research unveiled a unique cement-based material with an ultra-high strength, along with self-sensing and de-icing capabilities. Notably, the inclusion of CNFs in RPC led to significant improvements in compressive and flexural strength, reaching up to 117.1 MPa and 22.4 MPa, respectively, with just a 0.5% CNF addition. This enhancement in mechanical strength was attributed to CNFs bridging micro-cracks, filling pores, and accelerating cement hydration reactions. CNFs also curbed the formation and expansion of micro-cracks, resulting in a reduced porosity and refined pore sizes, thereby bolstering the mechanical properties of CNF-RPC. Furthermore, the researchers noted that incorporating 1.0% CNFs in RPC demonstrated an exceptional de-icing performance, showcasing promising potential for real-world applications, particularly in regions with colder climates.

Ousmane et al. [164] studied the possibility of using nanocellulose for ecological nano-engineered strain-hardening cementitious composites incorporating high-volume ground-glass-based pozzolans. This study showed how nanoscale cellulose filaments (CF) can be used as a novel tool for tailoring the properties of strain-hardening cementitious composites (SHCC) by incorporating high-volume ground-glass pozzolans (HVGP), in particular to attain an improved strength and ductility. Naskar et al. [165] explored the impact of nanomaterials on geopolymer concrete, specifically nano-silica, carbon nanotube, and titanium dioxide at varying percentages. Their investigation aimed to understand how these nanomaterials influenced the concrete's properties. The study found that incorporating 1% titanium dioxide led to a notable enhancement in compressive strength without significantly altering the pH level, which remained consistent across all cases. Their findings suggested that adding nano silica and titanium dioxide to low calcium fly ash-based geopolymer concrete could yield satisfactory compressive strength results. The presence of nanoscale particles appeared to create nucleation sites, fostering the formation of additional reaction products and resulting in a denser microstructure with stronger particle bonds. Similar to ordinary Portland cement (OPC), certain nanomaterials such as nano-silica acted as pozzolanic admixtures, improving the workability and flowability of the geopolymer concrete mix. This enhancement facilitated the concrete's ability to fill intricate molds and achieve complex shapes.

Based on an experimental study on the effect of carbon nanofiber (CNF) content on the durability of concrete, Tengjiao Wang et al. [166] found that the shrinkage resistance of concrete can be improved by incorporating carbon nanofiber. They found that CNF can delay the shrinkage of concrete to reduce its shrinkage rate and this modification effect is significant at the early stage of 0 to 28 days. Carbon nanofibers act as nucleating agents during the cement hydration process. They provide additional surface area for cement particles to react, resulting in more efficient cement hydration. As a result, the overall water demand for the mix can be reduced while maintaining the desired workability. A lower water-to-cement ratio leads to decreased drying shrinkage upon curing. The high aspect ratio and small size of carbon nanofibers facilitate better particle packing in the concrete mix. The inclusion of carbon nanofibers (CNFs) in concrete results in a denser microstructure with reduced voids and capillary pores, which, in turn, limits moisture pathways and minimizes shrinkage. CNFs also enhance frost resistance, with their modification effect becoming more pronounced with increasing freeze–thaw cycles. However, it is worth noting that incorporating too high of a volume fraction of CNFs can reduce the modification effect on permeability. In studies, it was observed that, when the volume fraction of CNFs was kept at 0.3%, the resulting nano-fiber-reinforced concrete (CNFC) exhibited the lowest permeability. Moreover, CNFC with varying CNF fractions showed a better carbonation resistance compared to Portland cement, with an optimal effect seen at a CNF volume fraction of 0.3%. This improvement in carbonation resistance became more significant with an increasing carbonation age. Furthermore, CNFs play a crucial role in bridging all parts of the concrete, limiting micro-crack development, improving micro-morphology, and filling internal pores. This process refines the pore structure, enhances compactness, and reinforces the integrity of the concrete, resulting in an improved overall performance and durability. Carbon nanofibers act as micro-reinforcements at the nano-scale level. Their uniform dispersion within the concrete matrix leads to a more homogeneous distribution of reinforcing elements, thereby significantly improving the durability of concrete.

In a news from the forest product laboratory, scientists shared an article named Nanocellulose and Concrete: A Happy Marriage, in which the incredible advantages of these tiny plant building blocks are vividly described [167]. Generally, nanocellulose is derived from renewable plant-based sources and consists of cellulose fibers at the nanometer scale. When incorporated into concrete, it brings out a set of desirable advantages that could potentially revolutionize the properties and performance of the composite material. As nanocellulose is strong but less dense, and also features a huge surface area, a thimbleful of this material has as much surface area as a 2800-square-foot house! The article describes the Moffett Creek Bridge in Siskiyou County, California, which is the first real-world application of cellulose nanocrystal-infused concrete. Furthermore, it was shown that only five gallons of nanocellulose was needed to increase the strength of the bridge by 20%. Another article [168] discusses the influence of Nylon 66 nanofibers-carbon nanotubes (CNT) hybrids on the mechanical strength and microstructure of hardened cement. From the results obtained, CNT-Nylon 66 hybrid nanofibers were identified as promising candidates to reinforce cementitious material due to the increase in the mechanical strength (28 days of curing) of hardened cement pastes (up to 43%, 30%, and 12% increases in tensile strength and toughness, respectively). The increase in mechanical strength was attributed to the bridging effect and the good linking of nanofibers with cement hydration products in the microstructure of hardened cement pastes. The CNTs act as a nanoscale reinforcement, while the Nylon 66 nanofibers are considered as agents providing a microscale bridging effect. This multi-scale reinforcement also enhances the bridging effect and energy dissipation, thus preventing crack propagation, also increasing the composite's ability to withstand loading and deformation. In addition, the researchers observed from their mechanical strength measurements that the Nylon 66 nanofibers helped to increase the tensile strength by 30%, compressive strength by 8%, and toughness by 49% by introducing Nylon 66 nanofibers. It was also observed that relatively stronger bonds were formed by the bridging effect of nanofibers among cement hydration products. As a consequence, a higher tensile strength, toughness, and ability to withstand deformation were observed. Here, the interaction of carbon nanofibers and PVA (micro-scale) fibers, at different scales, were assumed to play complementary and synergistic roles in enhancing the mechanical properties of the test specimens [169] The synergistic actions of nano- and micro-scale reinforcement could also be attributed, in part, to the contributions of nanomaterials to the interfacial bonding and pull-out behaviour of the microscale fibers within the matrix. Carbon nanofiber also offers distinct features for the effective reinforcement of cementitious matrices in the pre-crack and post-crack regimes. A hybrid system comprising unmodified carbon nanofiber at 0.145 vol.% of anhydrous cementitious materials (0.04 vol.% of concrete) and steel fiber at 3.55 vol.% of anhydrous cementitious materials (1.1 vol.% of concrete) provided balanced gains in the engineering properties of ultra-high-performance concrete [170].

Alumina-nano-fibers-reinforced concrete (ANFRC) offers exceptional mechanical properties, self-healing capacity, ultra-high durability, and the ability to withstand aggressive exposure scenarios, which makes it an attractive material choice for a wide range of applications, including high-stress structural elements, marine environments, and infrastructure projects in areas with severe weather conditions or chemical exposure [154]. ANFRC also possesses self-healing capabilities, allowing it to autonomously repair micro-cracks and minor damage that may occur during its service life. The small size and dispersion of alumina nano-fibers enable them to bridge small cracks and participate in the autogenous healing process, improving the overall durability of the concrete.

8. Conclusions and Future Perspectives

In summary, generally, the addition of recycled textile waste to concrete can positively affect its strength and mechanical properties. Textile waste can primarily act as a filler material, thus contributing to the enhancement of the concrete's compressive and flexural strengths. Optimal dosage levels from 0.5% to 5% of recycled textile waste in concrete can result in strength increases from 15% to 30%, notably improving the compressive and flexural strengths.

Conducting comprehensive lifecycle assessments (LCAs) and environmental impact analyses can also provide a holistic understanding of the environmental benefits and potential drawbacks associated with using recycled textile waste in concrete production, including energy consumption, emissions, resource depletion, and waste generation throughout the product's life cycle. LCA helps to identify environmental hotspots or critical stages in the life cycle of FRC, where significant impacts occur, which allows for targeted interventions, process optimizations, and mitigation measures to address environmental challenges and enhance the sustainability of FRC production and utilization. This knowledge will guide decision-making processes and support the adoption of sustainable waste management practices. Comprehensive LCAs can lead to targeted interventions and process optimizations, resulting in a 20% to 30% reduction in the overall environmental impacts throughout the concrete product life cycle. A cost–benefit analysis should assess the economic feasibility of using recycled fibers, considering the costs of additional processing, transportation, quality control measures, and potential savings from resource conservation and waste reduction. A thorough cost–benefit analysis can demonstrate a potential 10% to 20% cost savings from resource conservation and waste reduction, making recycled fibers in concrete economically viable. Conducting performance tests on FRC specimens with recycled fibers can assess their mechanical properties, durability, and long-term performance compared to conventional FRC. These empirical data are crucial for validating the suitability of recycled fibers in achieving the desired concrete properties.

Furthermore, it has been observed that the inclusion of textile waste can also improve the durability and resistance to cracking of concrete structures. In this context, nanofibers also hold great promise for enhancing the performance of fiber-reinforced concrete. Their unique properties can significantly contribute to improving the mechanical strength, durability, and functionality of concrete structures. Continued research and innovation in this field will undoubtedly lead to the widespread adoption of nanofiber-reinforced concrete in various construction applications. However, extensive study and continuous progressive attempts to explore the areas with a lack of knowledge need to be further studied. Continued research and innovation in this field are expected to lead to widespread adoption in various construction applications, further advancing sustainability practices in the construction industry.

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