

Review Article

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A review of microscopic characterization and related properties of fiber-incorporated cement-based materials

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Abstract: Fiber-reinforced concrete (FRC) has apparent benefits over traditional cementitious composites and possesses a great prospect in civil engineering projects. Previous studies reported that fiber admixtures could effectively enhance the mechanical properties, impermeability, and durability of cementitious composites. Nevertheless, the trade-off of the reinforcing efficiency, cost, and properties of the cementitious composites in different aspects has been a challenge in the application of FRC to practical engineering. This article summarizes a review concerning the recent development of FRC enhanced by different fibers and mainly focused on the fiber-reinforcing effects on the microstructure and the corresponding properties of cementitious composites. The addition of a small amount of fiber material has a significant change in

the microstructure and related properties of cement-based materials, but the presence of fibers also causes structural damage and other problems. The direction of future development of some cutting-edge technologies such as coating and hybridization methods on fiber modification was concluded to assist further research in FRC. This review will further enhance the understanding of fiber for reinforcing cementitious composites.

Keywords: fiber-reinforced cement, microstructure, mechanical performance, durability, fiber modification

1 Introduction

Cement has become the most widely applied engineering material in civil engineering due to its low cost, good workability, convenient construction, high initial strength, and wide range of sources [1]. However, with the drawbacks such as low tensile strength [2], low toughness [3], and susceptibility to cracking [4], cementitious composites have long been plagued, resulting in poor durability and high maintenance costs [5]. To prepare cementitious composites with higher strength and toughness, researchers have developed many different strengthening methods, such as nano modification technology [6], adding admixtures [7], *etc.* Some researchers have also proposed strengthening cementitious composites through fiber modification technology [8]. Over the past decade, fiber modification techniques have demonstrated the potential of fiber materials to enhance the physical and mechanical properties of cementitious composites, including reinforcing the interface structure [9], strengthening the mechanical properties [10], and bridging the visible cracks [11] in cementitious composites, which has a wide range of applications in practical engineering projects [12]. Presently, fiber enhancement modification of cementitious composites has been identified as one of the engineering research frontiers [13].

The theoretical research on fiber-reinforced concrete (FRC) began in the 1910s [14]. The early use of fiber was

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mainly steel fibers [15]. In 1911, H. F. Porter first proposed the concept of “steel fiber” concrete [16]. From 1911 to the 1940s, the United States, Britain, and other countries successively obtained some related patents but they were not applied in actual engineering. In the 1960s, Romualdi *et al.* published a theoretical research report on FRC [17], significantly impacting the development of fiber-reinforced cementitious composites. During the same period, other fiber materials, such as glass fibers [18] and carbon fibers [19], were gradually developed and applied to practical engineering materials [20]. With the development of the chemical industry, synthetic fibers, such as polypropylene (PP) fiber, polyvinyl alcohol (PVA) fiber, *etc.*, appeared in cementitious composites in the 1970s [21]. In the mid-1970s, several developed countries successively started the research and development of non-asbestos fiber-reinforced cement products [22]. In 1996, the 3rd International Cement Concrete Report Conference was held in China, which indicated that the research and application of FRC had been internationalized. In the early twenty-first century, improvements in fiber production technology promoted the development of high-performance, low-cost FRC materials. The wide application of various fibers in cement reinforcement has greatly promoted the development of the entire civil engineering industry [23].

Fiber can significantly improve the mechanical properties of cementitious composites [24] and reinforce the interfacial structure through relevant strengthening mechanisms [8]. The primary enhancing mechanism is the fiber bridging effect [25], which can inhibit crack propagation and bridge cracks. Different fibers also have their own unique enhancing mechanism [8,26]. For example, the enhancing mechanism of the steel fiber-reinforced cementitious composites stems from the combined action of physical and chemical adhesion between fiber and matrix [27]. The hydrophilicity of steel fiber promotes the hydration reaction around and the interface bonding, encouraging the hydrated product to grow and optimize the microstructure [27–29]. The chemical inertness of PP fiber only enhances hydration [30,31], and its low melting point allows it to reduce spalling of cement-based composites at high temperatures [32,33]. The PVA fiber enhances the bond between it and the interface through its good cohesiveness and water retention, enhancing the interfacial transition zone in the cementitious composites’ matrixes [34]. Basalt fibers are mixed with the cement slurry to produce a gel that fills the pores and enhances the interfacial transition zone [35].

The microstructure, mechanical properties, permeability-related performance, and durability of the cementitious composites after fiber modification have been significantly enhanced. For example, the tensile properties of cementitious composites modified by steel fibers are significantly improved [36], and the microstructure of the interfacial transition zone is

also significantly enhanced [37]. PP fibers can also enhance the mechanical properties of cementitious composites. According to most studies, the improvement of tensile strength can reach up to 36.23–40.73% [38]. The addition of PVA fibers will continue to improve the fracture toughness of cementitious composites, and their strength index shows a trend of first increasing and then decreasing [39]. The cement-based material reinforced by modified natural fibers shows good mechanical properties and interfacial strength [40]. Nylon fiber has sufficient alkaline resistance, which can significantly improve the tensile strength (up to 35%) and fracture performance of mortar, and turn the brittle failure into ductile failure [41]. However, fiber modification also has disadvantages for cement-based materials. For example, steel fibers and PVA fibers would reduce the durability of cement-based materials [42,43]. PP fibers and PVA fibers tend to agglomerate at high doses. Basalt fibers have an adverse effect on the fluidity of the slurry [44].

Overall, fibers have both advantages and disadvantages for the reinforcement of concrete, and fiber reinforcement technology is still an area that urgently needs to be further studied and it is necessary to gradually apply the latest research to engineering practice in the future [12,45]. However, the current research on various fibers is intricate and needs to be summarized, and the future development direction of fiber reinforcement technology needs to be clarified. Therefore, the existing research results, especially the results in recent years, are sorted out and summarized, and the future research direction of fiber reinforcement technology is prospected to make this review. The purpose of this review is to provide a comprehensive overview of the existing research on fiber-modified cement-based materials, mainly steel fibers, PP fibers, PVA fibers, and basalt fibers, supplemented by glass fibers, polyethylene fibers, *etc.* The microstructure of the modified cement-based composite material was studied emphatically, and its mechanical properties, fluidity, durability, and other performance indicators were discussed and summarized. On this basis, the treatment methods such as fiber coating and hybrid fibers to improve the adverse effects of fibers are proposed, and the future development of fiber modification technology is a prospect.

2 Steel fibers

2.1 Microstructure characteristics

The hydrophilicity of steel fiber promotes the hydration reaction of the surrounding cement paste and promotes

interfacial bonding. The hydrophilicity of the fiber will cause more water to gather around it, promote the hydration reaction, and hydration nucleate to form hydration products [28], and the hydrated cement paste will fill a large part of the space between the fibers and the cement matrix, promoting interfacial bonding [46]. As shown in Figure 1a, the hydrophilicity of steel fibers also promotes the hydration reaction of the surrounding slurry [28], the surface of cement slurry containing steel fibers is smoother and denser than ordinary slurry, and the interfacial transition zone is dense and complete, while the cement-based material containing steel fibers contains more C–S–H gels. These gel joints are embedded with each other and tightly

wrap various hydration products to form a continuous phase, filling the pores in the matrix, and reducing the cementitious material, the size of pores and microcracks significantly [47]. As the curing age increases, the microstructure of the interfacial transition zone between the steel fiber and the cement slurry will become denser, the degree of hydration will be higher, and the bonding performance will be better [48]. As shown in Figure 1b, Li *et al.* [28] found that the water absorption of steel fibers will cause more water to gather around, and make it hydrated and nucleated, and hydrates grow on the surface of the fibers, which promotes interfacial bonding. Other researchers have arrived at the same findings. For example, Hannawi *et al.* [46]

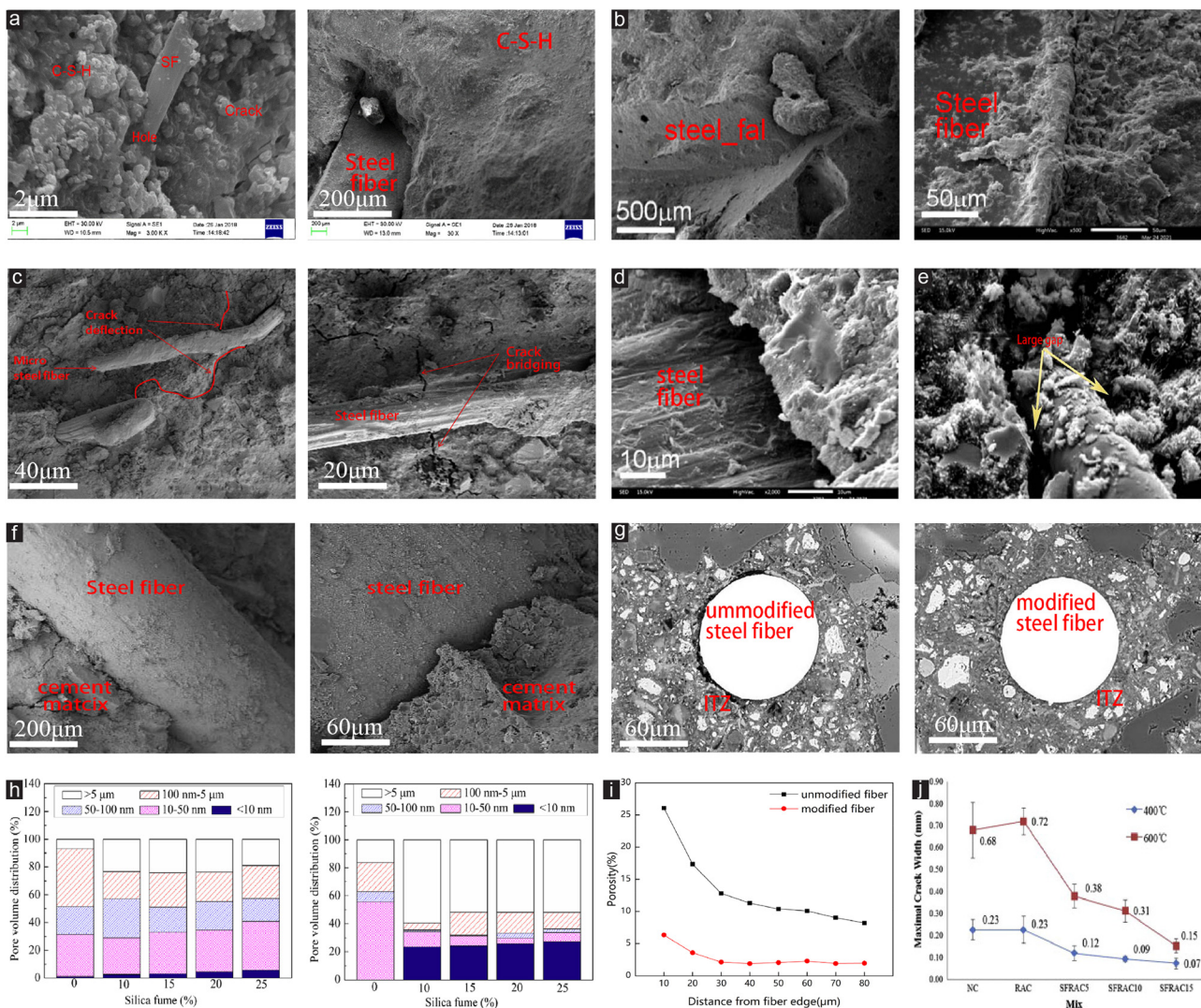


Figure 1: Scanning electronic microscopy (SEM) images of steel fiber incorporation and related pore changes. (a) The SEM image of the interfacial transition zone between steel fibers and the cement matrix [47]; (b) the SEM image of the interface between steel fibers and the cement matrix [28]; (c) the bridging effect of steel fibers [49]; (d–f) the interfacial transition zone when fibers are pulled out [28,50,51]; (g) the interfacial transition zone before and after steel fiber modification [52]; (h) pore distribution of FRC [48]; (i) the porosity before and after modification changes away from the fiber [52]; and (j) the maximum crack width of the specimen [53].

found that steel fibers have a more hydrophilic surface and that the hydration paste around the fibers can properly hydrate and fill a large part of the space between the fibers and the cementitious matrix. Li *et al.* [29] found that the hydrophilicity of steel fibers replenishes some free water, which forms a film on the surface of steel fibers, promotes the surrounding hydration reaction, fills the surrounding pores, and promotes interfacial bonding. Uygunoglu [37] found that the higher the degree of hydration, the more dense hydrated the cement paste covering the fiber surface; there is a good bond between the steel fiber surface and the hydrated cement matrix to form a dense matrix, further demonstrating the bonding properties of FRC.

After the steel fiber is hardened, there is a bridging effect, which can significantly delay the expansion of cracks and bridge macroscopic cracks. When steel fibers are treated at high temperatures and then cooled rapidly, the steel fibers are hardened and their tensile strength and durability are enhanced. As shown in Figure 1c, when the crack propagation intensifies, the steel fibers will be pulled out, and when the first crack microcracks appear, the fibers will start to bridge the crack and delay the increase in the crack width, causing the crack direction to change. When a secondary crack appears on the surface of the specimen, the bridging action makes the crack jagged and the fibers can effectively bear the load [49]. The fiber content also greatly affects the width of the primary crack, as shown in Figure 1j; as the steel fiber content increased from 0 to 1.5%, the average value of the maximum crack width decreased from 0.23 to 0.07 mm [53]. Other researchers have also reported the same findings. For example, Xu *et al.* [54] found that steel fibers embedded in the matrix bear the stress together with the cement matrix and play the role of a bridge, thereby delaying the expansion of cracks and improving the compressive strength. El-Hassan and Elkholy [55] reported that steel fibers increase the energy demand for crack propagation and bridge microcracks in alkaline-activated concrete, leading to a delay in the fracture process and improved post-crack properties. He *et al.* [47] found that the random distribution of steel fibers in the cement matrix creates a bridging effect, prevents crack propagation, and promotes more contact surfaces and a denser matrix, thereby increasing the compressive strength.

The microstructure of the interfacial transition zone of FRC has always been the focus of researchers. However, there are some differences in the research on the microstructure of the interfacial transition zone of steel fiber-reinforced cement-based materials. The mainstream research content is mainly divided into two types. One is that the weak interface adhesion between the steel fiber and cement paste leads to microcracks and pores in the interface

transition zone. Due to the internal bleeding of concrete, the free water gathers around the steel fibers, resulting in a looser interface area between the steel fibers and the cement matrix than other areas and there is a weak interaction between them, as shown in Figure 1d and e [28,50]. Under the conditions of wet curing, the cement matrix wraps the steel fiber. At this time, the pulling out of the fiber will result in some cracks caused by the mechanical stress in some interface transition zones. While the fiber pullout behavior was observed under dry curing conditions, the microstructure of the cured samples contained more debonding and microcracks due to the weak bonding effect between the fibers and the cement paste, and the quality of the interfacial transition zone was poor, as shown in Figure 1f [51]. Some scholars hold the same view, for example, Wu *et al.* [48] reported that the quality of the interface between the fiber and the matrix was poor due to the presence of a large number of microcracks and pores at the interfacial transition zone and the enriched orientation of CH crystals. The addition of 15–25% silica fume can effectively strengthen the microstructure between the fiber and the matrix, thereby enhancing the bonding properties between the fiber and the matrix. Igarashi *et al.* [56] showed that the presence of a “wall effect” above the steel fibers prevents cement particles from effectively accumulating on the surface of the fibers; this not only weakens the bond between the steel fiber and the cement matrix but also creates discontinuous pores on the upper and both sides of the fiber, and larger pores appear at the transition zone of the interface.

Some scholars have also found through experiments, simulations, and theoretical studies that fiber modification not only reduces the possibility of weak zone formation but also forms a denser microstructure at the fiber–matrix interface. As shown in Figure 1g [52], the modified steel fiber covers the multi-layer granular convex mold and the outermost layer of the multi-layer film has a large number of SiO_2 aggregation peaks on the microscopic scale, and SiO_2 reacts with Ca(OH)_2 at the same time. The generated $\text{CaO-SiO}_2 \cdot n\text{H}_2\text{O}$ tightly wraps the steel fibers, which significantly improves the interface around the fibers and increases the density of the area around the fibers, and its porosity is significantly lower than that of the cement matrix with unmodified fibers. It can also be seen from Figure 1i [52] that the porosity around the modified steel fiber is significantly lower than that around the unmodified steel fiber, and it decreases slowly with the increase of the distance from the modified steel fiber, while the porosity of the unmodified fiber decreases much faster. Silica fume also has a similar effect, as shown in Figure 1h [48]; as the content of silica fume increases, the proportion of micropores increases from 0.02 to 25%, and the

proportion of mesopores decreases sharply from 55 to 6%, while the capillary pores of 50 nm have a greater impact on cement-based materials, indicating that the addition of 15–25% silica fume strengthens the microstructure between the steel fiber and the matrix, reduces the porosity, and thus enhances the bonding performance. Similar findings have been made by other researchers. For example, Chang *et al.* [49] found that the combination of steel fibers and fiber-like hydration products can effectively reduce the thickness of the interfacial transition zone and bridge the cracks; Yuan *et al.* [57] proposed that the addition of appropriate steel fibers in concrete can effectively prevent microcracks caused by dehydration, reduce the size and number of cracks, and enhance the microstructure of the interfacial transition zone. Therefore, the porosity at the interfacial transition zone is the key to distinguishing whether steel fibers can enhance the microstructure of the interfacial transition zone. For a clearer understanding to the readers, we use tables to lists most of the above results.

2.2 Mechanical properties and workability

Steel fibers have an enhanced effect on the mechanical properties of concrete, mainly in tensile properties, and the improved efficiency within 1.5–2.50% is higher than that of other properties. As shown in Figure 2a, the compressive strength of concrete samples at 7 days of curing is

84.52% of that at 28 days of curing and all the compressive strengths increase with the increase of the fiber content. When the fiber content is 2.50%, the compressive strength is 13.25 and 15.72% higher than that of the control group M. This phenomenon is mainly due to the bridging effect of the fiber, which helps to transmit and bear the stress, thereby improving the compressive strength; the greater the amount of fiber added, the greater the contribution [54]. As shown in Figure 2b and c, the compressive strength and flexural strength of the sample are the same, both increase with the increase of fiber content, there is no inflection point, and it has a relatively stable improvement effect [54]. As shown in Figure 2d and e, under the conditions of micro-curing of ultra-high performance concrete specimens, the incorporation of fibers with different volume fractions will increase the early strength of the specimens. The flexural strength has a similar performance, and its early flexural strength is twice that of ordinary specimens [28]. Other researchers have arrived at similar results; for example, Ghazavi and Roustaei [58] found that the addition of steel fibers can increase the ultimate compressive strength of the soil by about 7 and 6% after the application of freeze–thaw cycles. However, in all cycles, reinforced samples with a steel fiber content of 2–3% have the greatest strength; 1–2% of steel fiber inclusions will not affect the frost heave but 3% of fiber can reduce the frost heave by about 20%. Xu *et al.* [54] found that as the steel fiber content increased, the compressive and tensile strengths also increased, and the

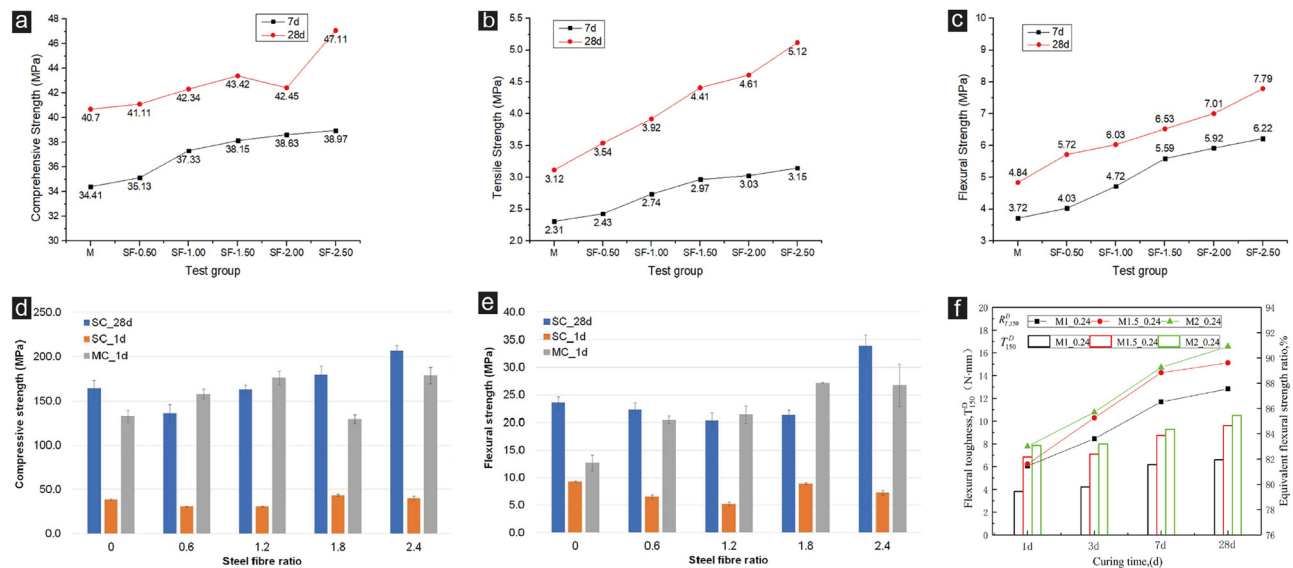


Figure 2: Changes in mechanical properties of concrete samples after incorporation of steel fibers. Changes in (a) the compressive strength, (b) the tensile strength, and (c) the flexural strength of the fly ash kaolin polymer recycled concrete after the addition of steel fibers at 7 and 28 days [54]. Changes in the (d) compressive strength and (e) flexural strength of all ultra-high performance concrete (UHPC) specimens with steel fibers added [28]. (f) Effect of steel fibers on the flexural toughness and ductility indices [49].

increase in the tensile strength was due to the compressive strength. El-Hassan and Elkholy [55] found that the addition of steel fibers can increase the compressive strength of 1 and 7 days by 39 and 52%, respectively, and the tensile strength and flexural strength increased by 31 and 25%, respectively, and with the increase of steel fiber content, the contribution is greater. Ibraheem *et al.* [59] reported that the impact of the steel fiber on the compressive strength is not great but when the steel fiber content reaches 0.75%, the tensile strength reaches the maximum value, and 0.5% steel fiber can increase the flexural strength by 13–44%. Zhu *et al.* [60] reported that the incorporation of recycled steel fibers may have a slight benefit on the compressive strength of the concrete but with a large fiber volume content, additional water is required to overcome problems related to workability, which may have a negative effect on the compressive stress resistance of the concrete due to increased porosity. Zhang *et al.* [61] found that, with the increase of the steel fiber content, flexural and splitting tensile strengths first increased and then decreased: A 1.5% steel fiber content can increase the compressive strength of the concrete by 18.5, and a 2.0% steel fiber content can increase the splitting tensile strength and the bending strength by 77 and 20%, respectively.

Steel fibers can improve the flexural toughness of cement-based materials and change the failure mode. As shown in Figure 2f, the flexural toughness of cement samples increases with the prolongation of curing time, and the increase of the fiber content also improves flexural toughness [49]. The increase of the steel fiber content not only has the above-mentioned effects but also can increase the elastic modulus of alkali-activated concrete gradually increase, and change the failure mode of the material from brittle failure to ductile failure. For example, Zhang *et al.* [62] observed that, during the elastic phase, the concrete bears most of the load, while the steel fiber hardly plays a role. In the inelastic phase, the steel fiber begins to bear the load and the role of concrete gradually diminishes. With a further increase of the yield strength to the hardening stage, the deflection strengthening rate is slower. This is because although the microcracks gradually increase into macroscopic cracks, the randomly distributed steel fibers significantly prevent the development and propagation of cracks through the bridging mechanism. The maximum peak load of steel fiber reinforced concrete (SFRC) increases with the volume content of the steel fiber. He *et al.* [47] reported that the addition of steel fibers changed the failure mode of recycled aggregate concrete (RAC) from the original brittle failure to ductile failure, which enhanced the flexural toughness of the sample; Yuan *et al.* [57] also mentioned that the incorporation of steel fibers into cement-based materials increased the strength and ductility of FRC, significantly

improved the failure mode of FRC, and transformed it from brittle failure to ductile failure. Ren *et al.* [63], in a study of UHPCC, found that after the addition of steel fibers, the concrete exhibited more ductile behavior in the cracking stage, and the interaction between the steel fibers and the matrix caused the ductile failure of the specimen, which remained almost intact after axial compression, and the fracture toughness increases significantly with the increase of steel fibers, and the fracture energy increases steadily with the increase of the steel fiber content. Mu *et al.* [64] observed that, with the addition of steel fiber, the ultimate freeze–thaw cycle of concrete significantly increased. The deterioration of concrete is limited, and the steel fiber improves its resistance to external loads, freeze–thaw cycles, and chemical erosion. Zhang *et al.* [65] reported that the steel fiber can effectively transform the failure form of concrete into ductile failure, thereby improving the tensile and splitting strength of concrete. But only when the steel fiber content reaches a certain threshold, can the tensile strength of concrete be effectively improved. Steel fibers also affect the bridging and cracking of concrete matrix; in addition, coagulation can improve the energy absorption capacity of the concrete. Therefore, the incorporation of steel fibers can effectively improve the mechanical properties of the cement matrix.

Steel fibers have an adverse effect on the workability of concrete, which is also the key to restricting the practical application of fiber-modified concrete. As shown in Figure 3a, Guerini *et al.* [66] found that the effect of steel fibers on the slump decreases linearly with the increase of toughness, and the effect of steel fibers is greater than that of synthetic fibers at a certain volume fraction. As shown in Figure 3b, Ibraheem *et al.* [59] found that after the addition of steel fibers, the workability of each group containing 0.75% steel fibers was reduced by 16% (OPC), 13% (GPCA), and 51% (GPCE), while those containing 1.5% steel fibers were reduced by 36, 41 and 58%, respectively. This is because the steel fibers absorb more bonding mortar due to their large surface area, resulting in a lower slump. Therefore, after the slump is reduced, more water and/or a higher dosage of superplasticizer should be added to bring the slump value as a measure of workability as close to the target value as possible [59]. There are many similar studies; for example, Köksal *et al.* [67] found that the increase of the steel fiber content has a negative impact on the workability of the sample, and it decreases with the increase of the steel fiber content; Mohod [68] studied the effect of steel fibers on the performance of concrete and found that with the increase of the steel fiber content, the workability of concrete decreased by 25%; and Hassan *et al.* [69] found that when the required water consumption was increased from 0.76 to 0.88% due to the reduction of slump after the

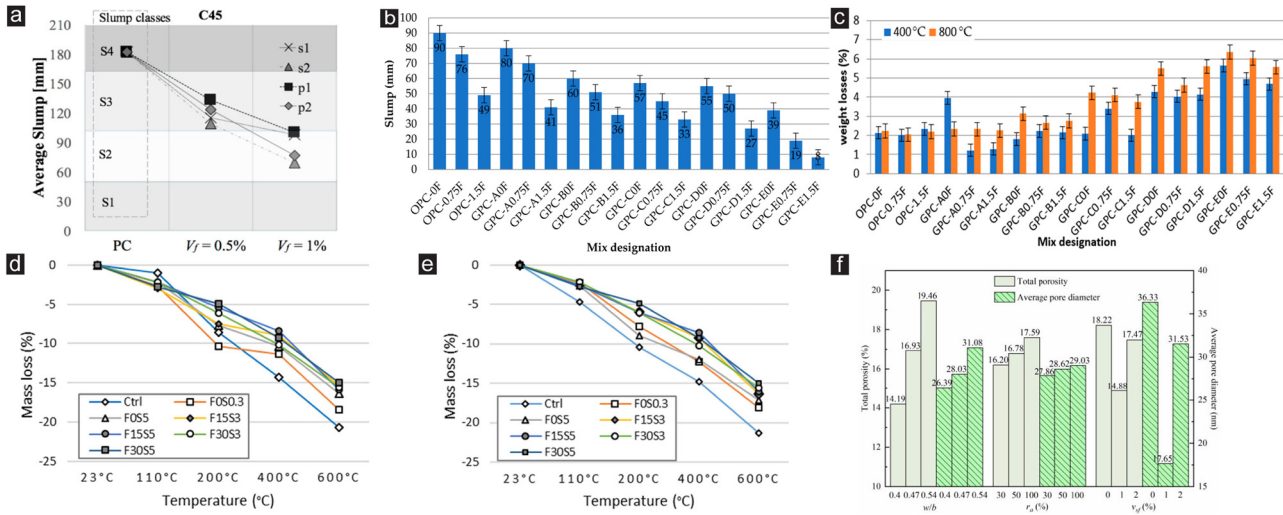


Table 1: Reinforcement effect of steel fibers on related properties of concrete

Refs	Steel fiber content (%)	Properties improvement
Xu <i>et al.</i> [54]	2.5	When the fiber content is 2.50%, the compressive strengths are 13.25 and 15.72% higher than that of the control group M
El-Hassan and Elkholy [55]	0–3	The addition of steel fibers can increase the compressive strength of 1 and 7 days by 39 and 52%, respectively
Ibraheem <i>et al.</i> [59]	0.5	0.5% steel fiber can increase flexural strength by 13–44%
Chang <i>et al.</i> [49]		The flexural toughness of cement samples increases with the prolongation of curing time, and the increase of fiber content also improves flexural toughness
Guerini <i>et al.</i> [66]		The effect of steel fibers on slump decreases linearly with the increase of toughness, and the effect of steel fibers is greater than that of synthetic fibers at a certain volume fraction
Ibraheem <i>et al.</i> [59]	0.75–1.5	The steel fibers will absorb more bonding mortar due to their large surface area, resulting in a lower slump
Mohod [68]		With the increase of the steel fiber content, the workability of concrete decreased by 25%
Hassan <i>et al.</i> [69]		When the required water consumption increased from 0.76 to 0.88% due to the reduction of a slump after adding more steel fibers and silica fume, and the lifting efficiency reached 15.79%
Yuan <i>et al.</i> [57]		As the volume content of steel fibers increases, the porosity and pore diameter of SFRRCs show a trend of decreasing first and then increasing

contact problem between the fiber material and cement interface greatly affects the mechanical properties and durability of the cement. How to optimize the interface contact has attracted extensive attention from researchers in recent years. Treatment methods such as fiber coating have been proposed one after another, but there are still relatively few studies in this area. Factors such as high prices and complicated operations limit the use of optimized fibers. Therefore, more high-quality methods are expected to be proposed in the future.

3 PP fibers

3.1 Microstructure characteristics

In contrast to the hydrophilicity of steel fibers, PP fibers are hydrophobic and chemically stable and do not participate in cement hydration reactions but only play a reinforcing role. Unlike steel fibers that increase the cracking strength, limit crack growth, and reduce crack width, PP fibers help produce materials with higher tensile strength, ductility, toughness, and durability properties [76]. As shown in Figure 4a, the addition of PP fibers enhances the cement hydration reaction, and the hydration products fill the pores, making the pore size and width of the interfacial transition zone smaller; however, due to the hydrophobic PP surface, the thickness of the water film in the interfacial transition zone between the fibers and the cement paste promotes the growth of crystals, and a large number of harmful crystals

adhere to the PP fiber surface, reducing the bond strength of the cement paste [47]. As shown in Figure 4b, Xu *et al.* [77] found that the PP fiber, as a hydrophobic material, has weak interfacial contact between the fiber and the cement matrix, which means that not all PP fibers can be effectively combined with the matrix, and the porosity of the interface transition zone containing PP fibers is higher than that of steel fibers; in addition, PP fibers are chemically inert and will not interfere with the cement hydration reaction. As shown in Figure 4c, Zabihi *et al.* [78] found that in 100% geopolymer mixtures, containing 0.3 or 0.5% PP fibers, the pores at the interfacial transition zone were refined, reducing water permeability, but microporosity and inhomogeneous microstructures can still be observed. As shown in Figure 4d, the bond between the PP fiber and the cement matrix is loose, and there are obvious gaps, which reduce the strength of the concrete. However, due to the chemical inertia of the PP fiber, the PP fiber does not participate in the hydration reaction, and the microscopic particles on the surface of the PP fiber bumps lead to an inhomogeneous fiber surface, creating a chain effect between the interfaces, which increases the interface strength [79]. Some scholars have also reached similar conclusions. Ranjbar *et al.* [80] found that the PP fiber, as a hydrophobic material, has a weak interfacial bond with the cement matrix, and air bubbles are trapped between the fiber surface and the corrugations of the matrix paste, over time, shrinkage causes the fibers to debond, widening the gap between the two. Kakooei *et al.* [81] reported that PP fibers are hydrophobic, which prevents them from being wetted by grout. The hydrophobicity of PP does not affect the amount of water required for concrete.

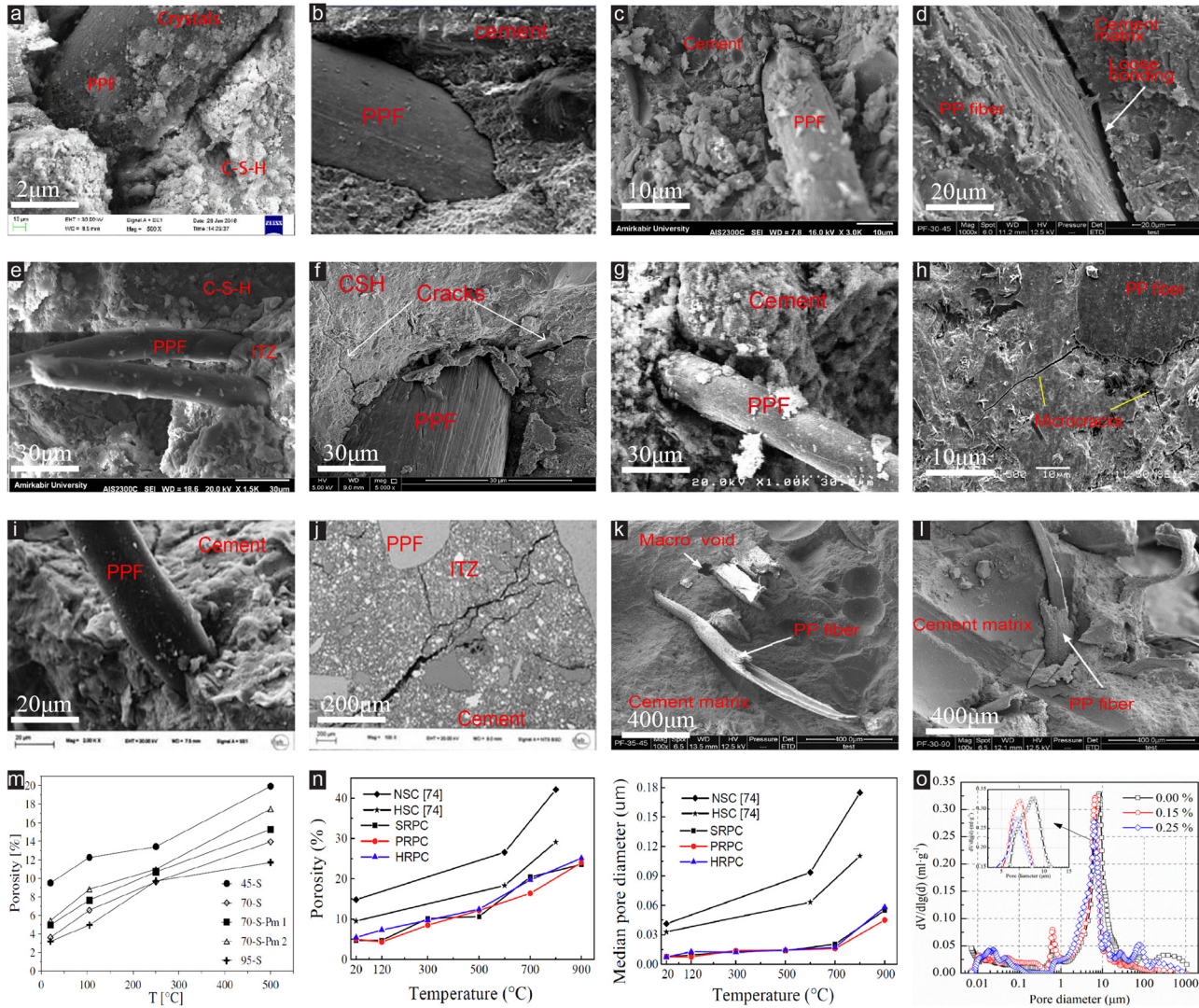


Figure 4: SEM images and related pore changes after PP fiber incorporation. (a–d) The interfacial transition zone between the PP fiber and cement matrix [47,77–79]. (e–g) Bridging effect of PP fibers in the cement matrix [82–84]. (h–j) Microscopic characterization of matrix containing PP fibers at high temperatures [85,86]. (k,l) Microscopic characterization between the cement matrix of PP fibers under two water/cement ratios [79]. (m–o) Changes in the porosity and pore size [86].

PP fiber hardening will have a bridging effect. Similar to steel fibers, PP fibers not only enhance the performance of the slurry but also prevent the development of cracks. As shown in Figure 4e, Mohseni [82] found that PP fibers can control cracks and reduce the number and width of cracks, which can prevent cracks from developing into macro cracks in cement-based composites; when crack propagation occurs and expands, the fibers can bridge cracks across cracks and prevent crack face separation. As shown in Figure 4f, Irshidat *et al.* [83] found that when the microstructure is deteriorated by heating the cement slurry, carbon nanotubes (CNTs) and PP fibers can alleviate this deterioration; CNTs fill these pores and integrate into the spacer wall and PP fibers bridge these cracks and slow their spread. As shown in Figure 4g, the PP

fiber improves the flexural strength by bridging across the cracks, and at the same time bridges the pores and cracks inside the concrete, preventing the cracks from expanding [84]. Other researchers have reported similar findings. Sukontasukkul [87], for example, argued that the real advantage of adding fibers is that after the matrix cracks and the fibers bridge these cracks and confine them. To deflect the beam further, additional force and energy are required to pull or break the fiber. Ahmad *et al.* [88] showed that the increase in the tensile strength is caused by the activity of fibers bridging in the cracks; the PP fibers first prevent the development of microcracks, and, after bending failure, the stress is transferred to the bridging fibers, which will delay cracking and increase the splitting tensile strength.

Most research on PP fibers involves the thermal effect of PP fibers at high temperatures. They believe that the increase in temperature will cause cracks, and the more the fiber content, the more microcracks; however, compared with plain concrete, fiber-containing concrete can bridge cracks and slow down the development of cracks. As shown in Figure 4h, Zhang *et al.* [85] found that at 150°C, the PP fibers remained intact and when the heat treatment reached 200°C, microcracks could be observed around the PP fibers and PP fiber channels, which was because of large thermal expansion before melting, the fiber will dissolve and produce cavities above 200°C, which does not confer UHPC with good peeling resistance. As shown in Figure 4i and j, Rossino *et al.* [86] found that the higher the PP fiber content, the higher the relative volume peak and porosity produced by heat treatment, as shown in the porosity vs temperature relationship (Figure 4m); the concrete has lower porosity at any temperature, but PP fibers lead to a significant increase in porosity above 250°C. As shown in Figure 4n, Abid *et al.* [89] studied the pore size and porosity changes in fiber-containing cement matrix materials at high temperatures and found that the porosity increases gradually with the increase of temperature; however, it is lower than that of the sample without fiber in each temperature range. As the temperature increases, the pore size change rate of the fiber-containing concrete sample is much lower than that of the plain concrete at or below 700°C, which is caused by the bridging effect of the fibers. Some scholars also hold this view. For example, Liu *et al.* [90] observed that the melting of PP fibers greatly affects the connectivity of pores, and the expansion of pores or cracks is the result of the increase of the internal pore pressure. Kalifa *et al.* [33] reported that, at a PP fiber content of 3 kg/m³, smaller and denser concrete appeared than plain concrete. Wang *et al.* [91] observed that when the content of PP fiber was 0.9 kg·m⁻³, the fibers formed a stable overlapping network structure inside the concrete, promoting the matrix microstructure to be smoother and flatter. When the PP fiber content reached 1.2 kg·m⁻³, it could not be well dispersed in the concrete, and the agglomeration of the fiber had an adverse effect on the dense structure inside the concrete.

However, some scholars have conducted research on PP fibers at room temperature and believe that an appropriate amount of fiber content is conducive to the refinement of pores, but if the fiber content is greater than 0.25%, the increase in fibers will lead to a sharp increase in porosity. As shown in Figure 4k and l, Yuan and Jia [79] studied cement-based materials containing PP fibers at different water/cement ratios and found that when the water/cement ratio was 0.30 (Figure 4k), as the PP fiber content increased

to 1.35%, PP fibers flocculate or agglomerate, which increases the weakest link in the internal structure of the material. The internal porosity will also increase sharply with the increase of the PP fiber content, which reduces the strength of the specimen and increases water absorption. At a water/cement ratio of 0.35 (Figure 4l), the number of pores and the amount of PP fibers increase, and when the fiber content is 0.90–1.35%, the diameter of macroscopic pores approaches or exceeds 500 μm, and a large number of pores with a diameter of 80 μm are also distributed near the pores. In the fiber content range of 0–0.25%, as shown in Figure 4o, the porosity of the specimens containing 0.15% fiber is much lower than the other specimens, indicating that the incorporation of an appropriate amount of fiber is beneficial to the refinement of the pore structure of the specimens, and the refinement of the pore structure contributes to the improvement of the performance. Other researchers have arrived at similar conclusions. For example, Liu *et al.* [92] reported that PP fibers can effectively reduce and inhibit the development of concrete micropores, prevent carbon dioxide and water from entering the concrete, and delay the carbonation rate of concrete. Adding an appropriate amount of PP fiber can significantly improve the carbonation resistance of concrete. Therefore, whether the content of PP fibers is appropriate is the key to judging whether PP fibers can enhance the microstructure of the interfacial transition zone.

3.2 Mechanical properties and durability

PP fibers have an enhanced effect on the mechanical properties of concrete, similar to steel fibers in terms of tensile and flexural properties, and tensile performance can be improved by 36.23–40.73%. As shown in Figure 5a, the elastic modulus increased by 11.78% for 0.1% PP fiber content, and then as the PP fiber content increased (from 0.1 to 0.3%), the elastic modulus increased ranging from 192.8 to 152.3 MPa, and the fitted curves on the graph show that the modulus of elasticity generally decreases with increasing fiber [93]. As shown in Figure 5b and c, it can be seen that the compressive strength increases slightly with the addition of PP fibers, and the tensile properties improve with the increase in fibers, with an increase of around 4% [78]. As shown in Figure 5d–f, Jun Li *et al.* [38] found that the PP fiber has a small influence on the compressive strength. With the increase of the fiber content, the compressive strength first increases and then decreases, respectively, increasing by 8.6, 7.7, and 4.7% compared with plain concrete. The addition of PP fibers can significantly improve the tensile strength, compared with plain concrete, *i.e.*, the

addition of PP fibers can increase the compressive strength by 36.23–40.73%, and the bending strength can increase by 48.83% at most. Moreover, if the PP fiber is distributed in a direction perpendicular to the force, the effect is more significant. Some scholars have also reported similar research findings. Tiwari *et al.* [94] found that the compressive strength decreased with an increasing concentration of the PP fiber content in the specimen. He *et al.* [47] showed that the addition of individual PP fibers reduces the compressive strength of RAC. The enhancement effect of PP fibers on the tensile strength of RAC showed a trend of first increasing and then

decreasing, and when the content of PP fiber was more than 0.9%, the improvement effect was negligible, and the flexural performance was similar to the tensile performance.

PP fibers have little effect on the durability of concrete. As shown in Figure 5g, Wang *et al.* [95] showed that the slump decreased by about 1.7 cm after the addition of PP fibers, and finally dropped to 18.3 cm. The workability of fresh mixes in which PP fibers are combined with rubber aggregates is further reduced, which is attributed to the friction between rubber particles and the fluidity limitation of PP fibers relative to the movement of coarse

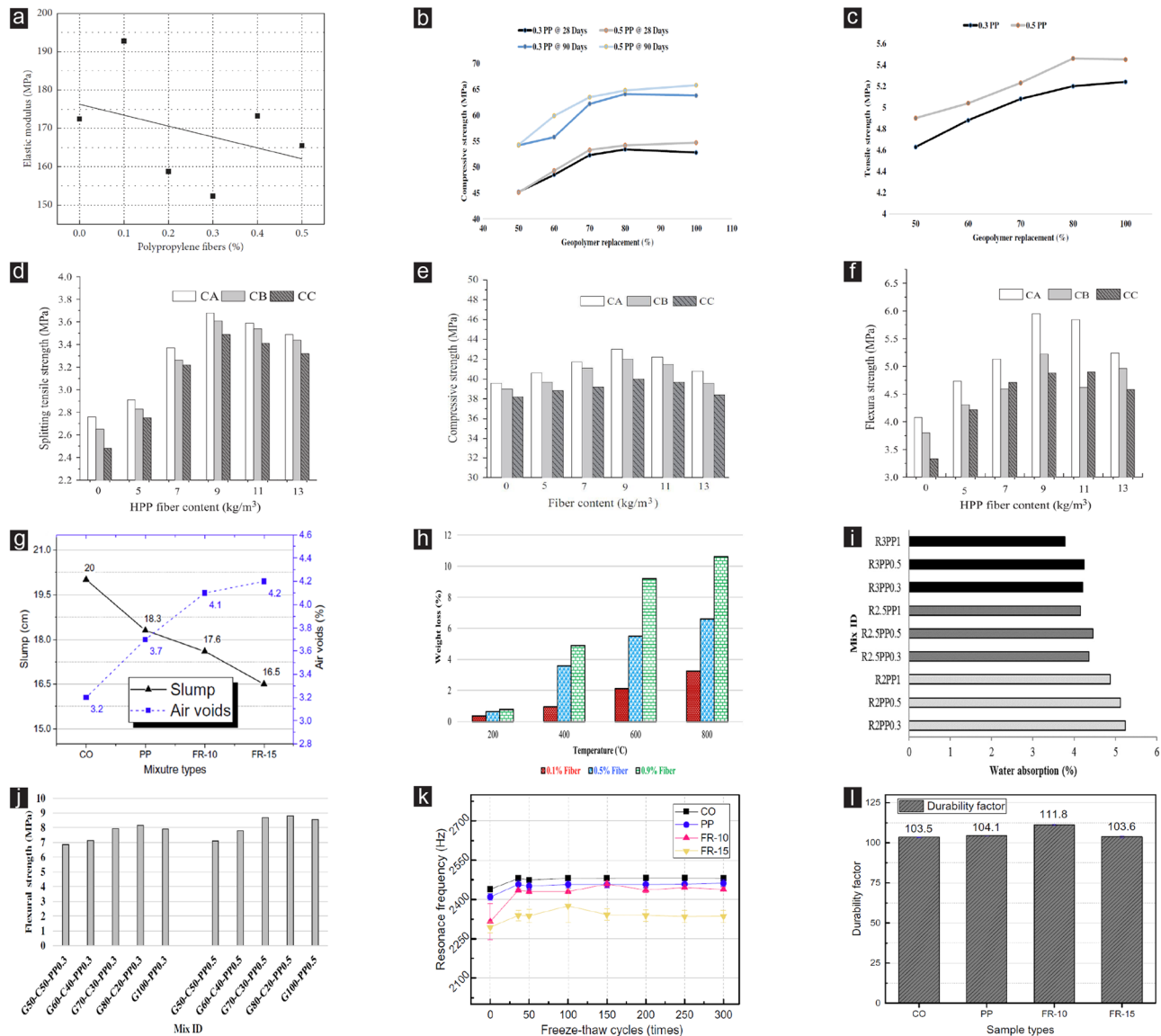


Figure 5: Effect of PP fibers on mechanical properties and durability of concrete. (a) Variation of modulus of elasticity with the fiber content [93]. Effect of different PP fiber contents on the (b) compressive strength and (c) flexural strength [78]. (d–f) Mechanical properties of concrete specimens mixed with different coarse aggregates at different fiber contents [38]. Effects of PP fibers on cement-based materials: (g) slump [95], (h) weight loss [96], (i–j) water absorption [78,82], (k) freeze–thaw cycles, and (l) durability [95].

particles, but the reduced workability is still maintained at a good level. As shown in Figure 5h, Hiremath *et al.* [96] found that as the temperature increases, the mass loss of FRC samples with different fiber contents increases, and the higher the temperature, the greater the mass loss as the fiber content increases. However, at 200°C, 0.5 and 0.9% fiber content has only 5 and 7% changes compared to the fiber mass loss of 0.1%, indicating that at room temperature, the fiber has little effect on mass loss. As shown in Figure 5i and j, it can be found that the presence of PP fibers has little effect on the water absorption of the specimen, and the overall fluctuation is not high [82]; however, when the PP fiber increases from 0.3 to 0.5%, the change in water absorption is negligible and the increase ranges from 1 to 8% [78]. As shown in Figure 5k and l [95], the resonance in the freeze–thaw cycle of the FRC specimen mixed with PP fiber samples decreased after the addition of PP fibers, indicating that the antifreeze performance of PP fibers was slightly improved. In the durability table in Figure 5l, the durability after the addition of PP fibers is about 0.58% higher than that of plain concrete, and there is almost no change. Others have arrived at similar conclusions. Xu *et al.* [77] showed that PP fibers facilitate the production of materials with higher tensile strength, ductility, toughness, and greater durability. Karahan *et al.* [97] observed that PP fibers reduce the workability of concrete. The addition of PP fibers to cementitious matrix materials also did not significantly improve the compressive strength and modulus of elasticity, and PP FRC had only a slight increase in the freeze–thaw resistance compared to concrete without fibers. Wang *et al.* [91] showed that, at 0.9% fiber content, the separation of broken cement blocks during wear damage can be inhibited, thus improving the wear resistance of concrete. Ghazavi and Roustaei [58] showed that PP fibers do not significantly affect the strength reduction caused by freeze–thaw cycles. The addition of 1–2% PP fibers to the samples augments the increase of the sample height to some extent. However, the addition of 3% fiber content to the clay samples reduces the height increase by 70% compared with those of unreinforced sample and this is a significant change.

3.3 Prospects for the application of PP fibers

As a kind of high-performance fiber, PP fibers have the advantages of high strength, good toughness, chemical resistance, and anti-microbial properties compared with steel fibers. Their chemical inertness prevents them from

participating in the hydration reaction and only enhances the hydration reaction, reducing the number of cracks, and preventing cracks from expanding. However, the performance of PP fibers in the durability of concrete is average. For example, the addition of PP fibers has little effect on workability, and the modulus of elasticity will decrease with the content of PP fibers, and their effect on the compressive strength is not significant. PP fibers are also recyclable materials that can be used to develop more sustainable building materials in the future [98]. They can also be used as a soil reinforcement material in underground engineering to increase the strength and stability of the soil [99]. At present, the main research focuses on the mechanical properties and microstructure of SFRC. It is found that PP fibers are more significant in terms of tensile strength and flexural strength and can reduce the expansion of cracks to a certain extent at high temperatures. However, there are few studies on the durability of PP fibers mixed into cement-based materials and the loose interfacial contact caused by the hydrophobicity of PP fibers itself, and the obtained theory is not enough to form a system. How to optimize the contact between PP fibers and the interface and alleviate the hydrophobicity of PP fibers has attracted extensive attention from researchers in recent years, and some treatment methods such as fiber coating technology have been proposed. However, there are still relatively few studies in this area. Factors such as high prices and complicated operations limit the use of optimized fibers. Therefore, more high-quality methods are expected to be proposed in the future.

4 PVA fibers

4.1 Microstructure characteristics

The PVA fiber is closely combined with the matrix to strengthen the interfacial transition zone. As shown in Figure 6a, Wang *et al.* [100] studied the microscopic interface between the PVA fiber and cement matrix at different temperatures and found that the PVA fiber and the matrix are tightly combined at room temperature, and the interface transition zone is strengthened compared with plain concrete. This adhesion effect is attributed to the hydrophilic hydroxyl groups in PVA. As shown in Figure 6b and c, Xu *et al.* [101] observed that, as the PVA content increases, the polymer film combines with the hydration products in the cement matrix to form a stable continuous network structure. While forming a continuous network

structure, a transition layer of the geopolymer film is formed at the interface between the PVA fiber and the matrix. The film more tightly bonded the interface between the geopolymer matrix and PVA fibers so that the PVA fibers can be more effectively distributed in the matrix. As shown in Figure 6d, Jiang *et al.* [42] observed that the surface of the modified PVA fiber after the addition of graphene oxide (GO) not only has a dense cement matrix microstructure but also has abundant hydration products attached. This shows that the modification of PVA not only improves the bonding between hydration products and PVA fibers but also facilitates the bonding between the PVA fibers and the cement matrix. Others have arrived at similar conclusions. For example, Sanaei Ataabadi *et al.* [102] found that the fiber links in the red area indicate that the fibers did not separate from the polymer matrix after the tensile loading cycle, but instead established a strong and suitable bond with the polymer matrix. In addition, the PVA fibers would intertwine with each other in one area, forming a continuous face that homogenized the composite and its rough surface caused more friction and bonding to the polymer matrix.

The PVA fiber has strong cohesiveness, which promotes the development of pores and cracks. As shown in Figure 6e and f, only a small amount of fibers were found in the mixture at lower PVA fiber dosages of 0.13 and 0.25%, while more uniform fiber distribution can be clearly seen in the FRC with a PVA fiber volume fraction of 0.5% (Figure 6e). When the fiber content reaches 0.75% (Figure 6f), the fibers appear flocculated due to uneven distribution, and a

large number of PVA fiber aggregation reduces the bond between the pulp and the fiber, and as the PVA fiber content increases, the number of cracks in the cement-based composites increases, and the porosity increases from 7.74 to 9.44% [103]. Some other scholars have reached similar conclusions. For example, Liu *et al.* [105] found that due to the high water absorption of PVA fibers, increasing the content of PVA fibers would cause more water to be absorbed, thereby increasing the porosity and pore connectivity. Xu *et al.* [106] found that PVA fibers tend to agglomerate during the stirring process, resulting in microcracks and pores in the slurry and reducing the mechanical properties of the matrix.

Although an increase in the PVA content leads to an increase in the number of cracks, the bridging effect of the PVA fibers delays the development of macroscopic cracks. As shown in Figure 6g, Fan *et al.* [104] found that with the incorporation of PVA, the internal structure, pore distribution, and pore size composition of the modified mortar changed. With the progress of the cement hydration reaction, the polymer is continuously precipitated in the cement to form a polymer film. These polymer membranes act as bridges between the pores together with the PVA fibers. As shown in Figure 6h, Liu *et al.* [105] found that the addition of more PVA fibers could strengthen the matrix. The PVA fiber is small enough to act as a bridge before the microcrack reaches the critical defect size, and the strong bond between the PVA fiber and the interface can also generate a large number of obvious microcracks, prevent the opening of macroscopic tips, delay the development of macroscopic

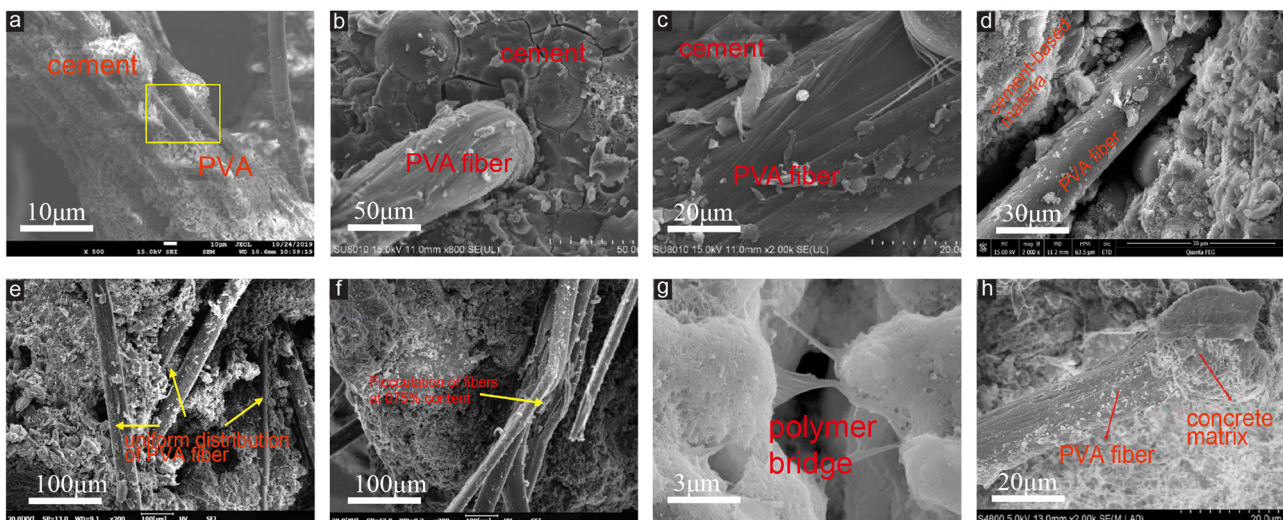


Figure 6: SEM images of cement-based materials containing PVA fibers. (a) The PVA fiber and cement matrix at room temperature [100]. (b and c) Destruction of PVA fibers due to bending cycles [101]. (d) Fiber morphology of PVA-modified samples [42]. Distribution of (e) 0.5% and (f) 0.75% PVA fibers in the composite [103]. (g and h) Bridging effect of PVA fibers [104,105].

cracks, and consume more energy. Other researchers have arrived at the same conclusions. For example, Noushini *et al.* [107] think that PVA fibers can play a bridging role in cement-based materials, sharing the load through the fiber and transferring it back to the matrix. Wang *et al.* [108] showed that randomly distributed PVA fibers can act as a bridge between microcracks and inhibit the development of cracks; meanwhile, elastic rubber particles can release the internal stress caused by freezing expansion, which helps to reduce structural damage. Sanaei Ataabadi *et al.* [102] showed that although the specimen failed and a crack appeared in the FRC specimen, the fibers still functioned, bridging the two sides of the crack. Therefore, ensuring that the PVA content reaches 0.5% is the key to judging whether the PVA fiber has a better reinforcing effect.

4.2 Mechanical properties and durability

Many studies have found that with the increase of the PVA fiber content, the strength index will first increase and then decrease, while the fracture toughness will continue to increase. As shown in Figure 7a, as the fiber content increases (0.13, 0.25, 0.5, and 0.75%), the fracture toughness of the composite increases by 80, 49, 86, and 125%, respectively, and the ductility of PVA fiber-containing materials is also enhanced compared to plain concrete [103]. In addition, Ca^{2+} and OH^- ions in the cement slurry are attracted to the PVA fiber, forming a $\text{Ca}(\text{OH})_2$ layer, which forms a strong bond between the fiber and the matrix [109]. As shown in Figure 7b, it can be clearly seen that with the addition of PVA fibers, the tensile strength is greatly improved with the improvement range being 7.4–44.4%; it reaches a peak when the fiber content reaches 0.5%, after which the enhancement effect of PVA fibers on the tensile properties of FRC will gradually decrease [103]. Compared with PP fibers, PVA has better compressive and bending properties, as shown in Figure 7c and d. Fan *et al.* [104] found that with the increase of the PVA content, the flexural strength of mortar first increased and then decreased, and the flexural strength of PCM3 containing 1% PVA fiber was the largest. Compressive and flexural strength enhancements are similar. Other researchers have reported similar findings. For example, Liu *et al.* [105] found that the addition of PVA fibers can improve the tensile toughness, and the lower the strength index, the higher the toughness. Sanaei Ataabadi *et al.* [102] observed that, at a volume fraction of 0.5%, the compressive strengths of PVA fibers at 28 days are 92.22 MPa; however, as the fiber content increases, the reinforcing effect of PVA fibers decreased significantly (from 92.22 to 78.27 MPa),

indicating that a 0.5% PVA fiber content is the best content for enhancing mechanical properties. The bending performance also has the same characteristics. The reinforcement effect of PVA fibers decreases from 31.20 MPa (0.5%) to 26.75 MPa (1.5%) and the reinforcement effect of 0.5% PVA fiber content reaches 49.5%. Zhang *et al.* [109] reported that PVA fibers have two opposite effects on the compressive strength of gel materials. The first is the strengthening effect; when the specimen is under pressure, the fiber effectively limits the crack growth caused by the transverse deformation of the specimen and improves the bearing capacity and ductility of the specimen. Another negative effect is that the addition of PVA fiber increases the initial defects of the matrix and reduces the bearing capacity of the sample. Under the coupling effect of a hot and humid environment and in the presence of chloride ions, the addition of 0.3% PVA fiber can maximize the compressive strength, and then the compressive strength decreases slightly.

The incorporation of PVA fibers had a negative impact on flowability due to the cohesiveness and water retention of PVA fibers. As shown in Figure 7e, as the PVA content increased from 0 to 0.75%, the flow diameter of the mortar decreased from 275 to 100 mm, especially when the fiber content reached 0.75%, and the slurry did not show any fluidity [103]. Sanaei Ataabadi *et al.* [102] found that increasing the PVA fiber content made the samples denser, while the fiber-absorbing resin made the samples less fluid. Fan *et al.* [104] found that the incorporation of PVA fibers greatly reduced the fluidity of mortar through slump tests. As the PVA content increased from 0 to 2.0%, the slump of the mortar decreased from 219.4 to 108.5 mm; compared with the mortar without fiber doping, when 0.2, 0.6, 1.0, and 2.0% PVA fibers were incorporated, the slump decreased by 13.9, 31.5, 41.1, and 50.5%, respectively. Some other scholars also hold the same view. For example, Liu *et al.* [110] reported that, with the increase of PVA content, the plastic viscosity of the modified cement mortar tends to increase gradually and is greater than that of unmodified cement mortar. Zhang *et al.* [111] noted that when the content of PVA fiber is 0.6% and the content of SiO_2 admixture is 1.0%, the mechanical properties and durability of geopolymer mortar are best enhanced.

The incorporation of PVA fibers will increase the water absorption and mass loss rate of the sample. As shown in Figure 7f, PVA fibers can increase water absorption by increasing the thickness and porosity of the transition zone, which can be increased by 3.45–4.16% compared with plain concrete [103]. Another study found that the PVA fiber reinforced concrete owns a higher water adsorption capacity than PP fiber reinforced concrete, and this adsorption capacity decreases with the fiber content increasing [102]. The permeability and mass loss rate of FRC-containing PVA fibers

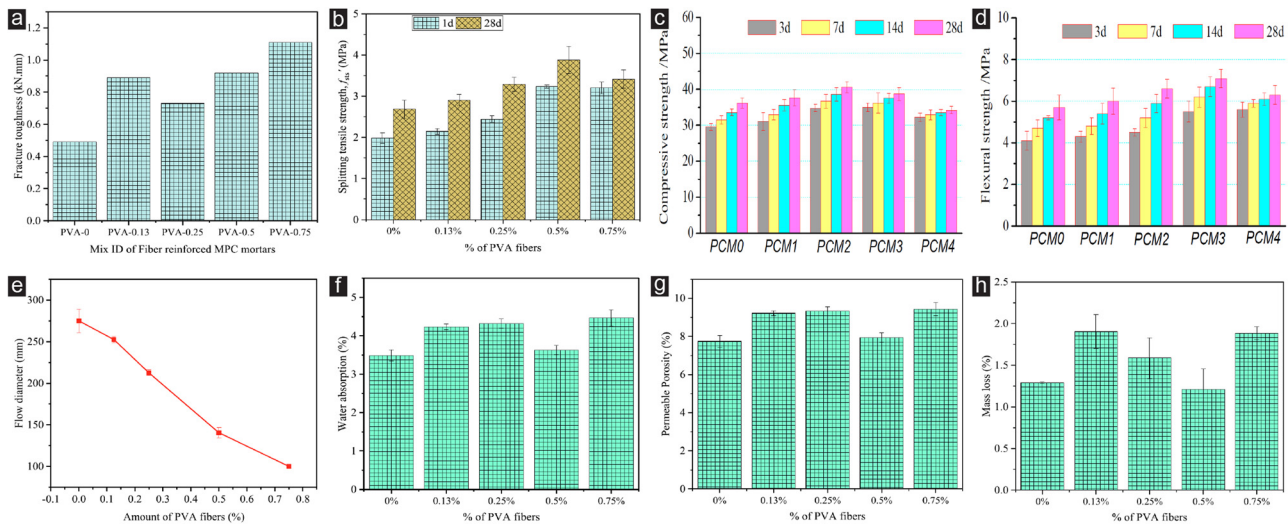


Figure 7: Effects of PVA fiber incorporation on related properties. Effect of PVA content on mechanical properties: (a) fracture toughness [103], (b) tensile properties [103], (c) compressive properties [104], and (d) flexural properties [104]. The increased PVA fiber content caused changes in durability [103], (e) fluidity, (f) water absorption, (g) permeable porosity, and (h) mass loss.

are also related to water absorption. As shown in Figure 7g and h, Dong *et al.* [103] found that the permeability porosity of FRC is higher than that of plain concrete, and the FRC containing 0.5% PVA fiber is slightly higher by about 2.45%. The 28-day mass loss of ordinary mortar without fiber is 1.29%, and after the addition of PVA fibers, the loss of the samples will increase, respectively, by 1.90% (0.13% PVA), 1.58% (0.25% PVA), and 1.88% (0.75%), while the mass loss of 0.5% decreased from 1.29 to 1.21%, which may be related to the uniform distribution and non-agglomeration of 0.5% PVA fibers. Other researchers have reported similar findings. For example, Fan *et al.* [104] found that the incorporation of PVA fibers greatly reduces the fluidity of mortar, and, due to the increase of PVA content there is an increase of interconnected pores. Guo *et al.* [112] observed that, in high-content FA concrete composed of nano-SiO₂ and PVA fibers, the dosage of nano-SiO₂ should be between 0.5 and 1.5%; the larger the PVA, the fluidity of concrete will be excessively reduced, which is not conducive to the dispersion of PVA fibers and affects the strength of the concrete.

4.3 Prospects for the application of PVA fibers

As a high-performance polymer, PVA fiber is mostly used as a modifier, an aggregate pretreatment agent, and a reinforcing agent for cement-based materials. Compared with other fibers, 0.5% PVA fiber has better enhancement effects on mechanical properties. At the same time, the high cohesiveness of PVA fiber itself also makes the bonding between it

and the matrix more compact and strengthens the interfacial transition zone. However, excessive PVA fibers will cause flocculation, which will lead to more cracks and pores in the interface transition zone with the matrix, reduce the fluidity of the slurry, and reduce the enhancement effect on mechanical properties. As a water-soluble fiber, PVA fibers can also be used to make sustainable building materials, such as biodegradable insulation boards [113]. Currently, most studies focus on using PVA fibers as modifiers and reinforcements for cement-based composites. There are a few studies on how to sustain the reinforcing effect of PVA fibers at large doses and reduce its negative effects on fluidity, and the obtained theories are not enough to form a system. How to improve its negative impact on workability and maintain its enhancement effect has received extensive attention in recent years. Treatment methods such as GO modification, hybrid fibers, PVA short fibers mixed with silica powder, and improved deflocculation efficiency through shear and vibration have been proposed but there are still relatively a few studies in this area, and factors such as high price and complicated operation restrict the use of optimized fibers, and so more high-quality methods are expected to be proposed in the future.

5 Basalt fibers

5.1 Microstructure characteristics

The mixing of basalt fibers promotes the production of cementitious substances and fills the pores. As shown in

Figure 8a, when the basalt fiber is increased from 0.1 to 0.3%, the microstructure will be dense first and then loose. When the fiber content is 0.2%, a large amount of white gel as $\text{Ca}(\text{OH})_2$ will appear on the surface of the basalt fiber, which is closely combined with the cement matrix, making the spatial structure more compact [114]. As shown in Figure 8b, the hydrophilic surface of the basalt fiber promotes better hydration of the cement paste around the basalt fiber, resulting in a dense hydrated cement matrix. The hydrated cement matrix not only adheres to the fiber surface but also fills the space between the basalt fiber and the matrix, forming a better interfacial transition zone [115]. Other scholars have also reached similar conclusions. For example, Xu *et al.* [44] found that the CSH peak of the slurry containing basalt fibers was higher than that of the slurry without basalt fibers, which indicated that the addition of high-calcium basalt fibers promoted the formation of additional gel, leading to the formation of a more uniform and dense matrix. Wu *et al.* [116] found that basalt fibers, as a SiO_2 -rich fiber, react with $\text{Ca}(\text{OH})_2$ to form an additional gel. Li *et al.* [117] showed that SiO_2 and Al_2O_3 contained in basalt fibers can chemically react with the alkaline substances inside the cement to form additional gels.

The presence of basalt fibers in the interfacial transition zone helps to form a relatively stable and interconnected structure inside the cementitious material. As shown in Figure 8c, it is found that when the FRC is subjected to external tension, the weakest interface transition zone in the concrete structure is first destroyed (Figure 8c). However, the presence of basalt fibers can effectively avoid and reduce the generation of cracks across the interface transition zone, and the support system formed by randomly distributed basalt fibers can further prevent the propagation of cracks [114]. As shown in Figure 8d, basalt fibers, as a SiO_2 -rich fiber, can be highly reactive with cement matrix. When the cement hardens, the basalt fiber will form an integral composite material with the cement matrix and work together to improve the mechanical properties and toughness of FRC [118]. As shown in Figure 8e and f, the basalt fiber is wrapped by the cement matrix, which makes the bond between the fiber and the cement matrix stronger. When the cracks expand further, the bridging effect of basalt fibers will consume a lot of energy and reduce the expansion of cracks. At the same time, the presence of basalt fibers also prevents cracks from breaking through basalt fibers, causing cracks to extend along the interface between basalt fibers and cement matrix, which consumes the energy for crack development and prolongs the crack propagation time to a certain extent [118]. Other researchers have reached similar conclusions. For example, Ma and Zhu [120] found

that when the cement matrix is damaged, the fibers act as bridges, delaying the formation and propagation of cracks.

The rapid propagation of the crack can lead to fiber pullout leaving holes or microcracks. As shown in Figure 8g, when the crack meets the basalt fiber, the crack rapidly expands along the interface between the basalt fiber and the cement matrix because it cannot break through the basalt fiber. When the expansion reaches a certain level, the fiber will be directly broken by the huge shear stress, and the fractured crack section is neat or slightly worn [118]. As shown in Figure 8h, when the crack continues to expand, the basalt fiber will be pulled out from the cement matrix, and a large amount of energy will be consumed in the pulling-out process. When the basalt fiber is pulled out, smooth and non-porous holes will be left, the surface of the basalt fiber is partially cemented, and scratch marks caused by the friction between the basalt fiber and the hard particles can also be observed at the end [119]. Some scholars hold a similar view. For example, Branston *et al.* [121] found that the poor post-crack response of basalt fiber specimens was attributed to failure due to fiber breakage. Therefore, the proper content of basalt fibers is the key to ensuring that it does not agglomerate and forms a relatively stable interior.

5.2 Mechanical properties and durability

With the increase of the basalt fiber content, the enhancement effect of mechanical properties showed a trend of first increasing and then decreasing. As shown in Figure 9a, Yang *et al.* [122] found that the enhancement of mechanical properties fluctuated with the increase in the fiber content, and the tensile and compressive strengths of the control samples were as high as 68.7 and 142.6%, respectively. However, as the amount of fiber further increased, the lifting effect decreased. As shown in Figure 9b–d, Zheng *et al.* [114] found that the optimum content of basalt fiber is 0.2%. When the basalt fiber content is 0.1%, the bridging effect of basalt fiber cannot be fully exerted, which affects the compactness of FRC, resulting in a decrease in compressive strength. About 0.2% basalt fibers will form a randomly distributed support system, reduce porosity, and increase compressive strength, of which the compressive strength at 28 days has increased by 11.25%. When the fiber content is too high, the fibers agglomerate and the compressive strength decreases (Figure 9b). The flexural strength is also similar (Figure 9c), and the growth rate of the flexural strength increases continuously when the basalt fiber content is lower. When the content is greater than 0.2%, the improvement effect is poor, and the

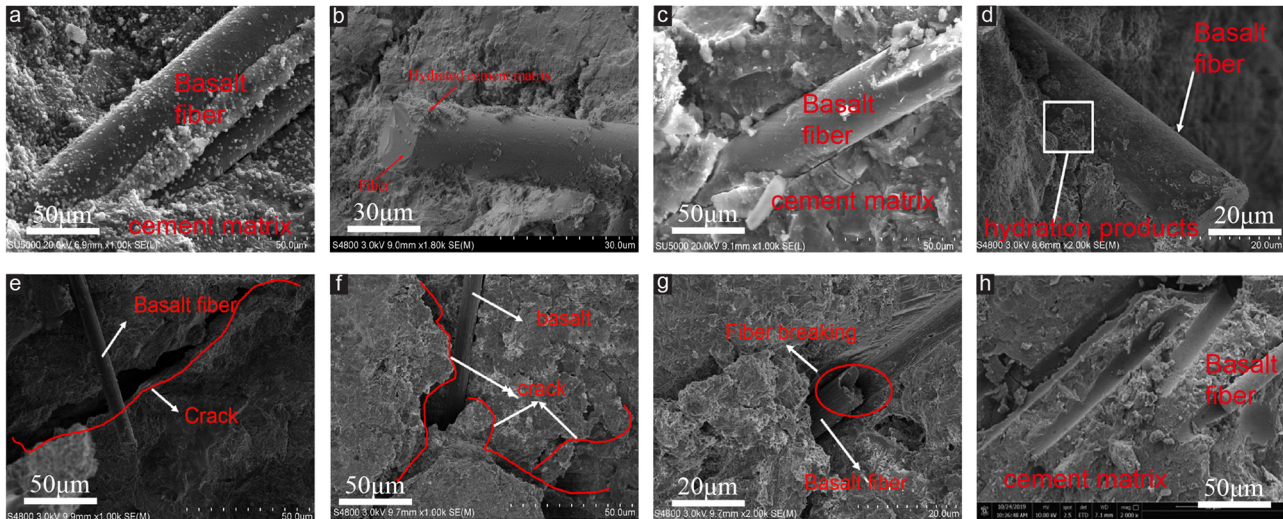


Figure 8: SEM images of cement-based materials containing basalt fibers. (a) Basalt fibers promote extra gel generation in FRC specimens [114]. (b) Hydrated cement matrix attached to the fiber surface [115]. (c and d) The interfacial transition zone between basalt fibers and cement matrix [114,118]. (e) Bridging effect of basalt fibers in FRC [118]. (f) Crack deflection in FRC containing basalt fibers [118]. The main causes of fiber failure in FEC are (g) fiber breakage [118] and (h) fiber pullout [119].

flexural strength of the sample mixed with 0.2% basalt fiber is 54.55% higher than that of plain concrete. The tensile strength (Figure 9d) is positively correlated with the basalt fiber content within 0–0.2%. When the fiber content increases to 0.3%, agglomeration will occur, resulting in the deterioration of the interface transition zone between the basalt fiber and the cement matrix and the decrease of the tensile strength. Other researchers have arrived at similar conclusions. For example, Wang *et al.* [123] found that the UCS of the specimens tended to increase at a fiber content of 0–0.2%;

however, at a content of 0.2–0.4%, the UCS tended to decrease, so the optimum content of basalt fiber suitable for embedding was 0.2%. Ma and Zhu [120] found that the compressive strength initially increases with increasing fiber content, reaches a peak at 0.3% fiber content, and then decreases with increasing fiber content; other mechanical properties also show similar effects. Zheng *et al.* [124] observed that the compressive capacity of fiber concrete is better than that of plain concrete but the improvement effect is very limited, less than 15%. When the content is too high, the

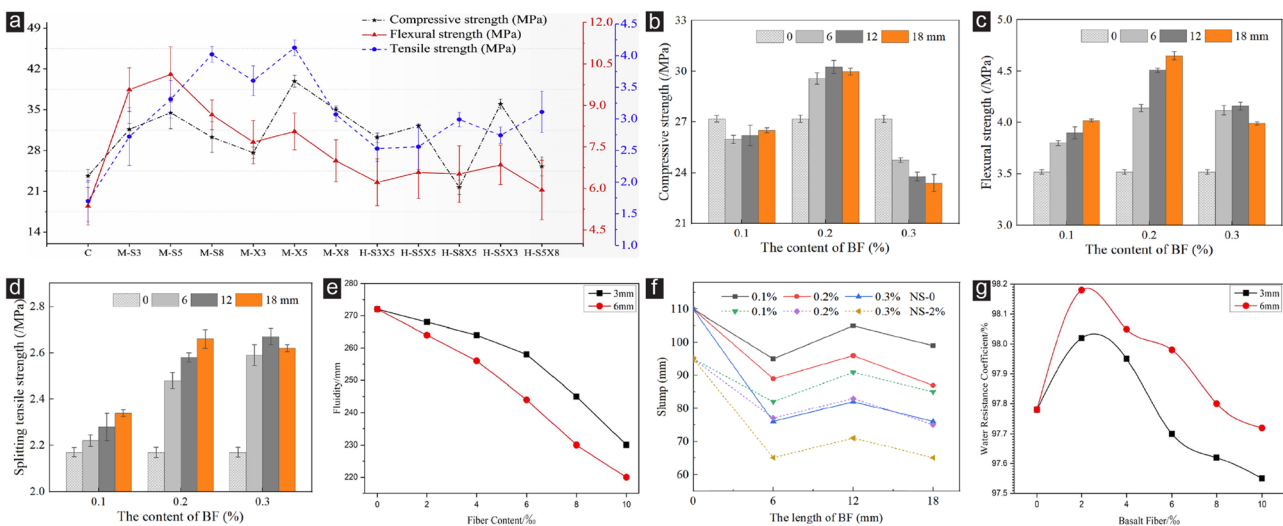


Figure 9: Changes in relevant properties after incorporation of basalt fibers. (a) Mechanical strength enhancement of basalt fibers and brucite fibers [122]. Effect of basalt fiber content on RAC mechanical properties: [114] (b) compressive strength, (c) flexural strength, and (d) tensile strength. Effect of basalt fiber content on (e) fluidity [44], (f) slump [114], and (g) water resistance [44] of FRC.

agglomeration of BF will reduce the fluidity of RAC, affect the compactness and cohesiveness of the mortar, and significantly reduce the compressive strength. This is because

- 1) BF absorbs part of the water originally used for cement hydration.
- 2) The inner compactness of concrete decreases between BF and concrete.

After BFRAC cracking, part of the fiber will slip, and the exposed fiber can only play the role of transferring load, and only the fiber wrapped by RAC can continue to work through the binding force between the mortar and the fiber.

Basalt fibers have an adverse effect on the fluidity of FRC. As shown in Figure 9e, as the content of basalt fiber increases, the fluidity of cement-based materials will decrease. At a concentration of 2–6%, the fluidity decreases slightly, and when the fiber content exceeds 8%, the fluidity decreases rapidly [44]. As shown in Figure 9f, when the basalt fiber content is 0–0.1%, the slump decreases slightly but the fluidity is not significantly affected, when the basalt fiber content is between 0.1 and 0.2%, the slump significantly decreases, and when it exceeds 0.2%, the slump does not change much but FRC basically loses its fluidity [114]. As shown in Figure 9g, with the incorporation of basalt fibers, the water resistance coefficient first increases and then decreases but the overall water resistance coefficient does not change significantly, indicating that basalt fibers have little effect on the development of water resistance [44]. Other researchers have arrived at similar conclusions. Al-Kharabsheh *et al.* [125] found that when the volume fraction of fibers increases, the slump decreases, and the workability will also decrease. This decrease may be due to the large surface area of basalt fibers, and the addition of basalt fibers increases the viscosity of new concrete and reduces the slump. You *et al.* [126] found that the addition of basalt fibers had a negative effect on the fluidity of the slurry, and the fluidity of the slurry decreased by about 30% with the addition of only basalt fibers.

5.3 Prospects for the application of the basalt fibers

Basalt fiber is an inorganic non-metallic fiber that is drawn from basalt ore after high-temperature melting through a drawing bushing under high-speed conditions. As a green and environmentally friendly new material, basalt fiber is a new type of reinforcement material in the field of geotechnical construction due to its excellent tensile

properties and good interfacial bonding properties with cement matrix, which has attracted the attention of many scholars. Mineral fiber is also an environmentally friendly material with good thermal insulation properties and may be used to develop higher performance and environmentally friendly thermal insulation materials in the future [127]. However, the current basalt fiber production technology is not perfect and its density is higher than other fibers, which has a poor impact on fluidity, especially in some strength problems that restrict the development of basalt fibers. At present, most of the research is still mainly on the reinforcement of cement-based materials in the form of chopped basalt fibers and reinforcing bars. There are few studies on how to improve the preparation of basalt fibers and the impact on fluidity, and the research results are not systematic. Methods such as using long basalt fibers, modifying basalt fibers themselves, and mixing them with other mineral fibers have been proposed, but at present, there are few researchers in this area, and problems such as high price and difficulty in preparation still hinder its further application. Therefore, better methods are expected to be proposed in the future.

6 Three relatively less studied fibers (polyethylene fibers, carbon fibers, and glass fibers)

6.1 Microstructure characteristics

Some fibers also have a reinforcing effect on cement-based materials, such as polyethylene fibers, carbon fibers, and glass fibers.

The incorporation of carbon fibers contributes to the formation of a relatively dense and interconnected interfacial structure. Tantray [128], by comparing the microstructure of samples under different fibers, found that 0.5–1.5% carbon fibers were evenly distributed and successfully bridged gaps and microcracks, as shown in Figure 10a. He also observed that carbon fibers can reduce the width of small cracks and play a role in strengthening the concrete soil layer. As shown in Figure 10b, the addition of carbon fibers provides nucleation sites for the formation of hydration crystals, and more hydration gels grow on the surface of the fibers and surround the surface of the carbon fibers, forming a denser microstructure on the carbon fibers. There are also relatively small grooves around the fibers that act as water channels, supplying the necessary water for the hydration process [129]. Some

scholars hold the same view. For example, Guo *et al.* [130] found that the pores of plain concrete are significantly larger than that of CFRC, and the carbon fibers are evenly distributed in the cement matrix, acting as bridges on the matrix.

The incorporation of glass fibers will optimize the interface structure of cement-based materials and reduce porosity. Yuan and Jia [79] found that when the water/cement ratio is 0.30 (Figure 10c), the glass fiber surface is covered by a firm cement matrix; at the same time, the glass fiber fills the pores in the interfacial transition zone to reduce the porosity and form dense and less porous microstructure. The glass fiber also prevents and delays crack propagation through the bridging. When the water/cement ratio is 0.35 (Figure 10d), the size and number of pores in the matrix increase with the glass fiber content. However, the bond between glass fibers and cement-based materials is still satisfactory because glass fibers can fill cracks and reduce cracks, and glass fibers with larger diameters can effectively connect larger pores.

The incorporation of polyethylene fibers results in a weaker interfacial transition zone. Due to the hydrophobicity of PE fibers, the fiber strength is usually not fully utilized, the frictional bonding with the cement paste is relatively weak, and fiber pulling out rather than fiber breaking is often observed, which can easily lead to larger crack widths [60]. As shown in Figure 10e, in 3DFRC, polyethylene fibers have a good distribution in the range of

pore sizes at room temperature, and can reduce the porosity and the number of large pores between printing layers; however, compared with 3D printing concrete without fibers, the total porosity is the highest [131]. As shown in Figure 10f, the average crack width of PE fibers was 138 μm but the average crack width of GO/PE fiber samples was 58 μm after GO incorporation, which was reduced by 60% [132]. Alrefaei and Dai [133] also found that cementitious composites containing polyethylene fibers had higher porosity due to the air-trapping effect caused by the addition of fibers compared to cementitious composites without polyethylene fibers, and the density is also slightly lower than the corresponding matrix.

6.2 Mechanical properties and slump

All three kinds of fibers are not as good as steel fibers in terms of reinforcement performance but they still have better effects than plain concrete. Xiao *et al.* [131] found that the compressive strength of polyethylene fiber-reinforced 3DP samples was about 20–30% higher than that of samples without fibers. After high-temperature heating, due to the low melting point of polyethylene fibers, polyethylene fibers still play a reinforcing role before 400°C, as shown in Figure 11a. Flexural performance has a similar effect. As shown in Figure 11b, compared with the sample without fiber, the flexural strength of the sample with fiber

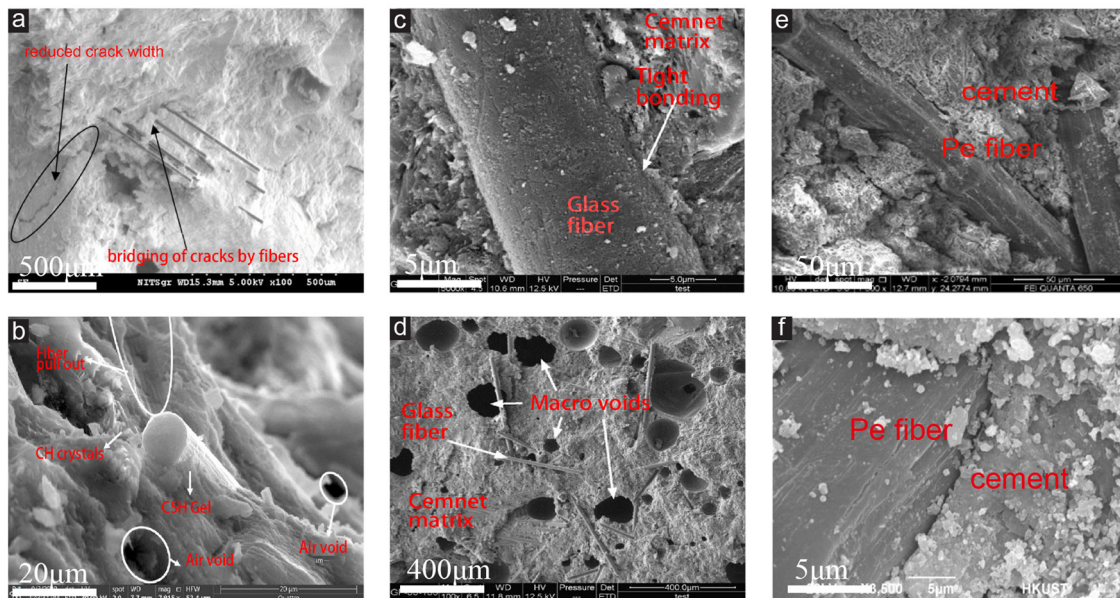


Figure 10: SEM images of three fibers incorporated into cement-based materials. (a) Carbon fiber bridging effect [128]. (b) SEM image of carbon fibers in the cement matrix [129]. SEM images of glass fiber-containing cement-based materials with water/cement ratios of (c) 0.30 and (d) 0.35 [79]. (e–f) Interface microstructure between cement-based materials and polyethylene fibers [131,132].

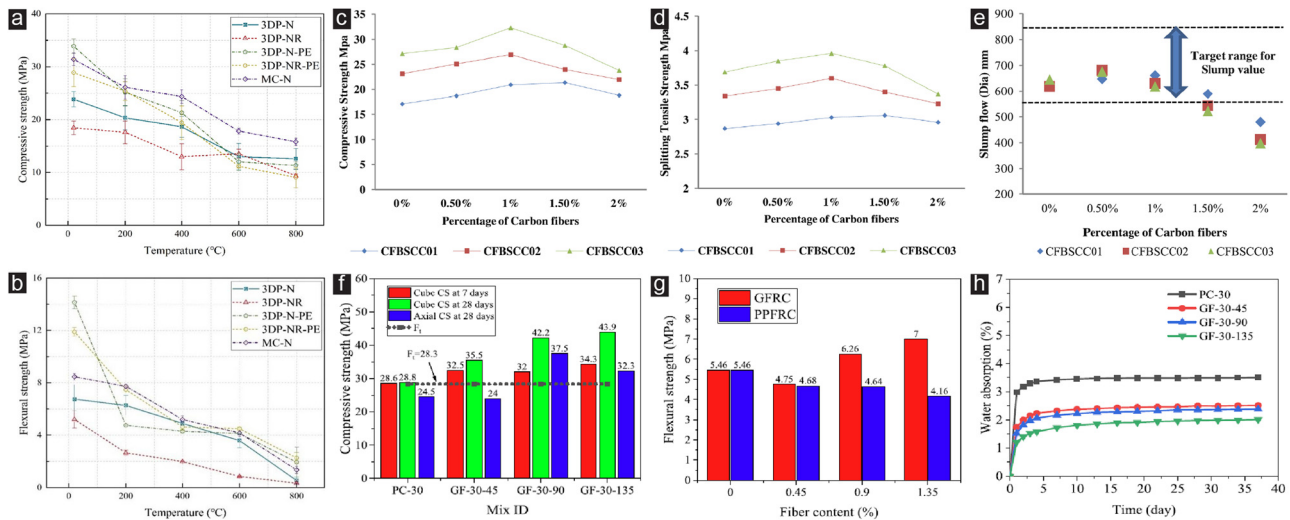


Figure 11: Effect of different fiber incorporations on relative properties. (a and b) Mechanical properties of cement-based materials containing polyethylene fibers [131]. (c and d) Mechanical properties of carbon fiber-containing cement-based materials [128]. (e) Slump of carbon fiber-containing cement-based materials [128]. (f–g) Mechanical properties of cement-based materials containing glass fibers [79]. (h) Water absorption of cement-based materials containing glass fibers [79].

can be increased by 109.4 and 128.6%, respectively. As shown in Figure 11c and d, Tantray [128], by studying the effect of carbon fiber incorporation on the mechanical properties of SCC, found that the change in the compressive strength depends on the percentage of carbon fiber and its distribution in the SCC mixture. When the carbon fiber content is 1 and 1.5%, the maximum increase in the compressive strength is 24.5%; the tensile strength also increases with the increase of the carbon fiber content and the maximum increase in the tensile strength reaches 6.62%. However, the strengthening trend of the compressive strength decreased above 1.5% fiber content. Yuan and Jia [79] found that glass fibers can significantly increase the compressive strength (Figure 11f) and flexural strength (Figure 11g) of concrete. As the content of glass fiber increases, the compressive strength increases significantly, and when the content of glass fiber is 1.35%, it increases by about 52%. The bending resistance also increases significantly with the increase of glass content, and when the glass fiber content is 0.90%, the bending resistance increases by about 28.2%. Some scholars also hold the same view. He *et al.* [134] found that polyethylene fibers can enhance tensile strength, changing it from highly brittle failure to relatively ductile failure. Guo *et al.* [130] found that the compressive strength of 1.0% carbon fiber doped at room temperature was up to 15% higher than that of ordinary concrete. Akbar *et al.* [129] indicate that by the addition of 0.25% of finely ground recycled carbon fiber, the flexural strength of cement-based materials will increase to 9.36 MPa, an increase of nearly 33.5%; the flexural strength of cement composite

materials with the addition of 0.5 and 1% recycled carbon fiber will increase to 10.12 and 12.76 MPa, respectively.

Both glass fibers and carbon fibers have an adverse effect on the fluidity of concrete (Figure 11e) Tantray [128] shows that although the slump increases slightly at lower fiber contents, the slump worsens at higher carbon fiber contents. This results in lower fluidity of the slurry because of poorer distribution at higher carbon fiber content. As shown in Figure 11h [79], due to the good hydrophilicity of the glass fiber, the cement matrix and the glass fiber are closely bonded, and, at the same time, the bonded and hardened hydrated cement product on the surface of the glass fiber has the effect of filling the pores. Therefore, the increase of glass fiber content will significantly reduce the water absorption rate of the sample and reduce the fluidity of the sample. Other researchers have reached similar conclusions. For example, Guo *et al.* [130] found that the increase of the carbon fiber content significantly reduced the fluidity and workability of concrete. Cohesion and water retention are significantly improved, and the improvement becomes more pronounced with increasing carbon fiber content. The larger volume fraction of polyethylene fiber will also reduce the slump but there are only a few studies at present.

6.3 Prospects for the application of carbon fibers, PE fibers, and glass fibers

Polyethylene fibers, carbon fibers, and glass fibers, as excellent non-metallic fibers in the market, have been

widely used in the fields of safety protection, aerospace, and electronic transportation and have attracted the attention of many scholars. However, there are a few important fiber-reinforced materials in the field of construction engineering. Although these three fibers have good effects in enhancing the mechanical properties and microstructures of cement-based materials, their immature preparation process, slow production capacity growth, high cost, and reduced slurry fluidity, especially the glass fiber in the human body, is harmful and other reasons limit its development. At present, most of the research is focused on enhancing its mechanical properties, and how to improve the preparation process and fluidity is less researched and fragmented. Fiber surface treatment can be an effective solution to enhance fiber/matrix interaction [60]. Carbon nanofiber, GO, and silane coupling agent coatings have been physically applied to improve interfacial properties [60]. In addition, some methods have been proposed, such as preparing activated carbon fibers, hollow carbon fibers, using ultra-high molecular weight polyethylene fibers, and using two-time forming-crucible drawing to produce glass fibers. However, problems such as difficulty in preparation and high cost still hinder its further development, and more high-quality methods are expected to be proposed in the future.

7 Conclusions and outlooks

Fiber modification technology has demonstrated the potential of fiber materials in enhancing the physical and mechanical properties of cement-based composites and improving the interface structure. Studies have shown that the incorporation of small amounts of fiber materials (steel fibers, PP fibers, PVA fibers, mineral fibers, *etc.*) has a significant improvement in the microscopic characterization and mechanical properties of cement-based materials. In the above studies, it was found that all these fibers have some common advantages, such as the bridging effect, which can effectively improve the interface transition zone and bridge macroscopic cracks. Among them, both steel fibers and PP fibers can enhance the hydration reaction of cement, and they have better enhancement effects on the tensile and flexural properties, and the improvement efficiency is between 30 and 60%. PVA fibers, basalt fibers, and carbon fibers are all tightly combined with the cement matrix at room temperature to form a relatively dense and stable internal structure. The enhancement effect of these three fibers and glass fibers on the mechanical properties showed a trend of first increasing and then decreasing. These fibers also have their unique characteristics, such as the following:

- 1) The steel fiber promotes hydration reaction and interfacial bonding of the surrounding cement slurry, which not only reduces the formation of weak areas but also forms a denser interfacial microstructure. In terms of related properties, steel fiber contents of 1.50–2.50% have the most significant performance improvement efficiency, as well as changing the failure mode of the material, improving bending toughness, and reducing its weight loss. In addition, some researchers also believe that it increases microcracks and porosity.
- 2) PP fibers being hydrophobic do not participate in the cement hydration reaction and only play a reinforcing role. It can also slow down the development of cracks at high temperatures. The improved efficiency of PP fibers on tensile properties is more significant, which can reach 36.23–40.73%. It has little impact on the durability of concrete and helps to produce more durable materials. When the content of PP fibers exceeds 0.25%, it will also lead to a sharp increase in porosity, increasing the weakest link inside.
- 3) The PVA fiber itself has a strong bond and can be closely combined with the interface. It was found that the distribution of 0.5% PVA fiber was the most uniform, the mechanical properties were enhanced the best, and the compressive properties were increased by 49.5%. In addition, the PVA fiber also increases the water absorption and weight loss of the sample.
- 4) Basalt fibers promote the production of cementitious substances through mixing and form a relatively stable and interconnected structure inside. At a fiber content of 0–0.2%, the improvement effect of basalt fibers on mechanical properties shows an upward trend, and then gradually decreases with the increase of fiber content. In addition, the rapid crack propagation of samples containing basalt fibers can lead to the formation of microcracks or fiber breakage.
- 5) Carbon fibers, glass fibers, and polyethylene fibers can reduce porosity and act to bridge cracks but polyethylene fibers form a weaker interfacial transition zone. The enhancement effect of the three kinds of fibers on the mechanical properties of fibers is the weakest.

Since the development of fiber modification technology, in addition to the above-mentioned individual problems, some common problems and challenges still hinder the development of fiber modification technology; for example, fiber preparation is difficult, the cost is high, and the sinking of the cement during the mixing process leads to uneven distribution and other recognized problems. There are also some problems with the fiber itself. For example, agglomeration or flocculation of polypropylene, PVA fibers, and

basalt fibers occurs at high content, which increases the weakest link in the internal structure of the material; steel fiber, polyvinyl alcohol fibers, basalt fibers, glass fibers, and carbon fibers all have adverse effects on the durability of cement-based materials. Although there are already treatments such as cladding techniques, fiber blending and the use of long-cut fibers that provide new ideas for the further development of fiber modification techniques, there are still problems such as high costs and difficulties in preparation. And the impact of these treatments on cementitious materials has not been adequately studied and is not systematic, so in the future, better quality methods are expected to be proposed.

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