

Review Article

Review of Basalt Fiber-Reinforced Concrete in China: Alkali Resistance of Fibers and Static Mechanical Properties of Composites

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Received 12 February 2018; Revised 22 April 2018; Accepted 10 May 2018; Published 21 June 2018

Academic Editor: Nadezda Stevulova

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Research on three-dimensional, randomly distributed BFRC in China is analyzed and summarized in relative depth in this study. The results indicate that the effect of the fiber component and alkali corrosion temperature on the alkali resistance of BF is significant; the BF has little effect on the compressive strength of the concrete; the tensile and flexural strengths of the composites significantly increase compared with plain concrete, and the fiber content has a significant effect on the strength. In light of some problems in the current research, six possible research topics are suggested: (1) investigating the alkali resistance of the BF under dynamic temperatures, lower alkali concentrations, and longer alkali corrosion times; (2) improving the alkali resistance of the BF by increasing its hydrophobicity; (3) determining the optimal fiber distribution orientation of the BF with various characteristic parameters; (4) establishing the calculation formulas for the critical content and critical aspect ratio of various types of BF; (5) determining the optimal mixture ratio of two or more fibers in the FRC while studying the complementary mechanisms between each other; and (6) improving the dispersion of the BF and the BF/matrix interfacial properties.

1. Introduction

Concrete, which is the most widely used material in civil engineering, has the advantages of high compressive strength and good durability. However, it also has the disadvantages of high dead weight, low tensile strength, poor toughness, low fracture energy, and poor impact resistance [1–3]. Concrete needs to be used in conjunction with other materials, which complement its properties, and thus, the application space will be expanded. Reinforced concrete and FRC are two of the most common building materials. The fibers used in such composites include steel fiber, carbon fiber, glass fiber, BF, synthetic fiber, and plant fiber [4]. Among them, as a new material in the 21st century [5], BF has a wide range of raw material sources, good thermal stability (the end-use temperature range is -263 to 900°C), thermal insulation (the thermal conductivity is approximately $0.04\text{ W}/(\text{m}\cdot\text{K})$), good environmental compatibility, high tensile strength, and high

elastic modulus [6–9]. Due to the mixing of BF, the internal structure of the concrete can be optimized; it can be reinforced and toughened, and its thermal insulation and durability can be improved, among other effects [10–13].

The Czech Republic began testing basalt wool as a substitute for asbestos at the end of the 1950s. The erosion resistance of the fiber and the bonding between the fiber and the cement were found to be effectively improved by adding alkali resistance components into the fiber and treating the surface with a polymer [14, 15]. The former Soviet Union made a step forward in their BF research and set out to investigate it in the 1960s. However, the publication of numerous patents and papers related to BF and large-scale production did not begin until the 1990s [16, 17]. The study of BF in Europe, the United States, Japan, and other countries started in the 1970s, and the production process was inferior to those in the former Soviet Union [5]. However, in recent years, in-depth research on BFRC has

been reported in Europe, the United States, and Japan, specifically reports on the alkali resistance of BF by Sim et al. [18] and Lipatov et al. [19]; the strength, heat resistance, high-temperature resistance, and inflaming retarding of BF glass aggregate concrete by Borhan et al. [20–22]; the thermal deformation of BF-aerated concrete by Sinica et al. [23]; the conventional mechanical properties of concrete with a high BF content by Ayub et al. [24]; and the wear-corrosion resistance of BFRC by Kabay [25], among others.

In China, in 1978, the Nanjing Glass Fiber Institute [26] first proposed the use of basalt to produce alkali-resistant fiber and enhance concrete. In the same year, Shen [27] conducted an experimental study on the alkali resistance of BF. In 1980, Du [28] summarized a report in the former Soviet Union's *Building Materials* about the advantages and engineering application prospects of BF. In 1990, Zhao [29] translated a brief report from the former Soviet Union entitled "Basalt Fiber Reinforced Concrete," which first introduced the concept of BFRC components. However, systematic reports on BFRC began in the early 21st century with the reports on the performance of BF, the research progress abroad, the wide application prospects of BF in the field of concrete, and other aspects of BF by Hu et al. [5, 30], Ye [31], and Wang and Zhang [32], among others.

Enabled by continuous improvements in the production process, BF has been incorporated into three-dimensional, randomly distributed FRC, fiber-reinforced polymer bars, fiber cloth, fiber grille, and other composite forms to address practical engineering needs. It has significantly improved the various properties of concrete. This paper mainly reviews the research progress that has been published in Chinese journals concerning the alkali resistance of BF and the basic mechanical properties of the three-dimensional, randomly distributed BFRC. The existing problems are noted and some are detailed, and specific research strategies are put forward, pointing out the direction to improve the aforementioned properties of BFRC. Due to space limitations, the impact mechanical properties, crack resistance, and durability of BFRC will be reported in another paper.

2. The Alkali Resistance of BF

Because concrete is alkaline, the alkali corrosion resistance of BF directly affects the adaptability and the properties of BF in the material. The literature [33] stipulates the alkali resistance of BF and requires that the filament-breaking strength retention rate of the BF used for concrete is not less than 75% after being exposed in the saturated $\text{Ca}(\text{OH})_2$ solution at 100°C for 4 h [34]. Therefore, studies of the alkali resistance of BF in terms of the properties of BFRC are both necessary and meaningful.

2.1. Research Progress. The alkali resistance of BF is mainly affected by factors such as the alkali concentration of the application environment, the alkali corrosion temperature, the alkali corrosion time, the properties of the fiber itself, and the pretreatment conditions, among others. In the nearly 40 years since Shen first studied BF in 1978 [27], experimental

studies on the alkali resistance of BF have mainly been focused around the aforementioned aspects. Because the physical and mechanical properties of current BF are much better than 20 years ago, research since 2000 is the primary body of work elaborated on in the following sections.

In 2004, Wang et al. [6] studied the chemical composition of BF and its surface modification with alkali solutions. Their results showed that the main chemical components of BF were SiO_2 , CaO , and Al_2O_3 , which played important roles in determining the chemical stability, mechanical strength, and thermal stability of the BF. After treatment with a 0.1 mol/L NaOH solution, the surface of the BF exhibited some defects, such as a tumor-like substance and corrosion pits, increasing the roughness and surface area. This effect led to a decrease in the fiber strength but improved the interfacial bond between the fiber and the matrix. In 2010 and 2015, Wei et al. [35] and Li et al. [36] analyzed the mechanism of the alkali corrosion of BF. The network skeleton structure of the fiber was mainly composed of Si and Al. In the alkaline solution, a substitution reaction occurred between the OH^- and $\equiv\text{Si}-\text{O}-\text{Si}\equiv$ in the fiber, resulting in dissolution of the Si element, cleavage of the silicate ion skeleton network, and destruction of other components in the framework. The OH^- diffused into the internal structure of the fiber, leading to lamellar spalling of the surface layer.

In 2006, Wang et al. [37] studied the alkali resistance of BF, which was produced by Heilongjiang Jingpo Lake Basalt Fiber Company, in an alkali corrosion environment of boiling 2 mol/L NaOH solution. Their results showed that the BF was mainly composed of Si, O, Fe, Ca, and other elements. After boiling for 3 h, the mass retention rate of the raw yarn and the strength retention rate of the fiber tow after dipping and curing were approximately 96% and 82%, respectively, indicating high alkali corrosion resistance capacity. The authors attributed this high capacity to the presence of alkali metal oxides in the BF.

In 2007, Huo et al. [38] investigated the alkali resistance of the BF filament and tow in an alkaline corrosion environment of 2 mol/L NaOH solution at 80°C . The model of the fiber, which was produced by the Shanghai Russian Basalt Fiber Co. Ltd., differed from that investigated by Wang et al. The tow was prepared by dipping in 648 gum epoxy. The results (Figure 1(a)) showed that the mass of the fiber decreased slowly with increasing alkaline corrosion time after soaking in an alkali solution. The mass retention rate after 24 h was approximately 88%. The fracture strength of the filament and tow after plying gum treatment rapidly decreased; their strength retention rate after 3 h was approximately 60%. These results indicated that the plying gum treatment could not improve the alkali resistance of the fiber over a short time. The microscopic appearance of the fiber after alkali corrosion exhibited significant pits due to surface spalling (Figures 1(b) and 1(c)). In addition, compared with the conditions used by Wang et al. [37], the experiment had a lower alkali corrosion temperature, and the reaction rate was correspondingly lower; however, the strength retention rate of the tow was lower, which might be related to the fiber component.

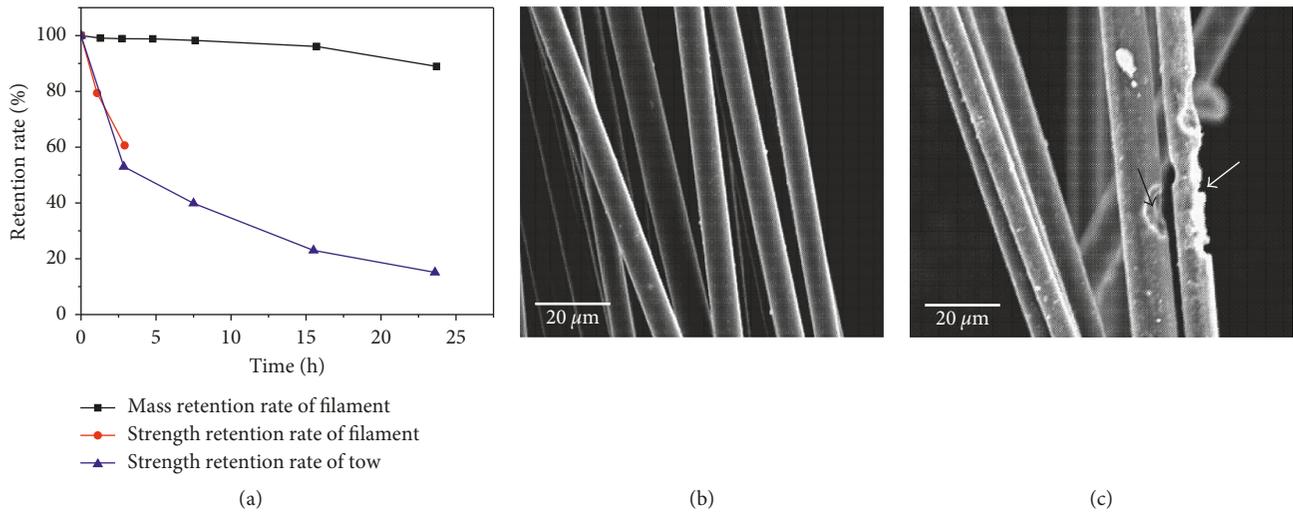


FIGURE 1: The alkali resistance of BF in 2 mol/L NaOH solution at 80°C: (a) curves showing the variation of the mass and strength of the fiber with increasing alkali corrosion time and SEM images of the fibers (b) before and (c) after the alkali corrosion [38].

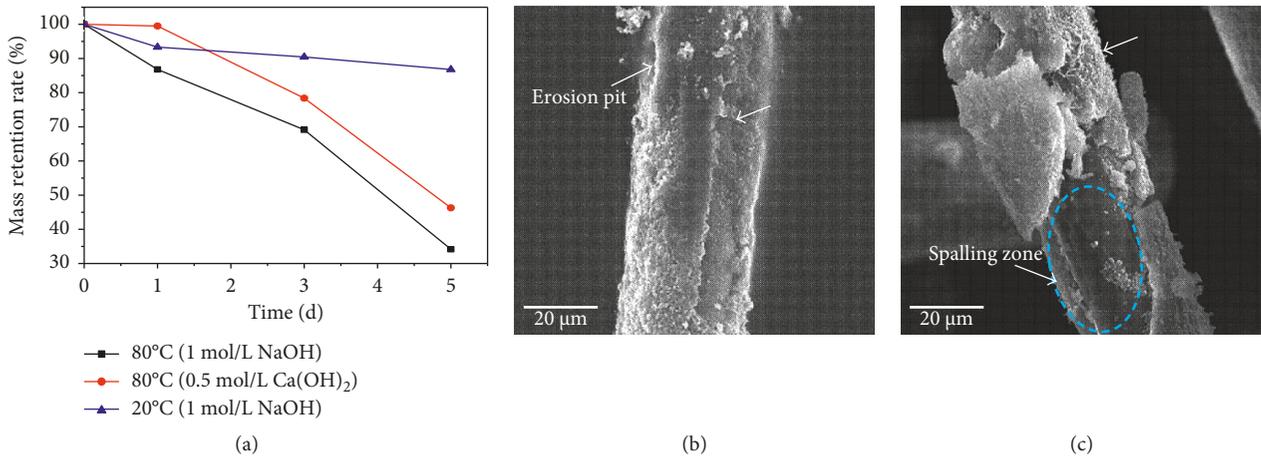


FIGURE 2: The effect of alkali corrosion temperature on BF. (a) The mass retention rate-alkali corrosion time curves at different temperatures and the alkali corrosion damage at (b) 20°C and (c) 80°C [39].

In 2010, Huang and Deng [39] studied the alkali resistance of BF at different alkali corrosion temperatures and longer corrosion times. They found that after being soaked in a 1 mol/L NaOH solution for 5 d (Figure 2(a)), the BF exhibited a mass retention rate of 87% when the temperature was 20°C; in addition, the corrosion degree was lower. However, the mass retention rate was only 33% at 80°C, showing significant corrosion and spalling (Figures 2(b) and 2(c)). The temperature strongly affects the alkali resistance of BF. In addition, compared with the results of Huo et al. [38], those of Huang and Deng [39] were obtained at the same alkali corrosion temperature (80°C) but at different concentrations of the alkali solution (1 mol/L and 2 mol/L), which gave mass retention rates of 87% and 89%, respectively; thus, the concentration of the solution had little effect on the mass of the BF under higher alkali concentrations.

In 2012, Wu et al. [40] studied the effect of alkali concentrations on the tensile strength of twisted BF with a single

diameter of 8 μm. The concentrations of NaOH solution ranged between 0.5 and 2 mol/L, and the alkali corrosion time and temperature were 3 h and 100°C, respectively. Tensile strength retention rate of fiber was determined according to GB/T 7690.3-2001, and the results (Figure 3) showed that the damage of alkali solution to fiber intensified with the increase in concentration, resulting in the fibrous weak surface and the sharp decline in strength. The strength retention rate of fiber was only 53.67% when the concentration was 2 mol/L, which was quite different from that of 82% obtained by Wang et al. [37] under the same condition. The distinction might result from the twisting treatment in addition to the different fiber contents.

In conclusion, the results in the aforementioned studies show that the influence of the fiber component, internal microstructure, alkali corrosion temperature, and alkali corrosion time on the alkali resistance of BF is significant. However, the effects of the fiber pretreatment and the increase in the alkali solution concentration under higher

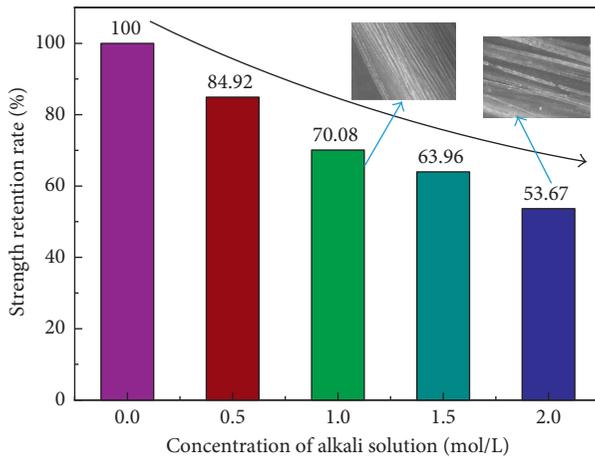


FIGURE 3: The effect of alkali concentration on the twisted BF [40].

alkali conditions have a limited impact on the alkali resistance. Therefore, in future research, well-directed studies are needed on the alkali resistance of BF and its adaptability based on the characteristics of the concrete. The aforementioned performance of BF can be improved through the fiber performance and the alkali corrosion environment.

2.2. Analysis and Prospects. On the basis of the review of the antecedent research results concerning the alkali resistance of BF and the application working conditions of BF in concrete, the following four research directions are put forward:

- (1) On the basis of the temperature variation curve as a function of the age of the concrete structure under the actual working conditions, the alkali resistance of BF needs to be measured and studied at the dynamic alkali corrosion temperature. Such a study will enable the mechanism of influence on the properties of the BFRC to be concurrently examined. In the current study, the alkali resistance of BF is studied at a constant temperature. However, in the course of hardening of the concrete, factors such as the concrete material properties, hydration heat, and casting temperature indicate that the temperature parabolically changes and tends to become stable with age. Moreover, different concrete structures with different measurement point locations show distinctly different temperature changes (Figure 4). In addition, the temperature will affect the alkali corrosion reaction rate and the alkalinity of the environment surrounding the fiber, which are important factors in studies of the alkali resistance of BF. Therefore, investigations of the corrosion resistance of BF under dynamic temperature are necessary to simulate the environment of concrete and to explore the mechanism by which BF modifies the mechanics, durability, and other properties of BFRC.
- (2) To study the adaptability of BF in the concrete, the alkali resistance of BF in a simulated alkali solution with a pH of 10.5–13.5 should be evaluated. Some

authors [41] have shown that the pH value of well-hydrated Portland cement was between 12.5 and 13.5, and the pH value of sulfoaluminate low-alkali cement was between 10.5 and 11.5. As a result, the pH value of concrete is lower than that. In the aforementioned studies, NaOH solutions with a concentration of 1 mol/L or higher were mostly used; the alkalinity of these solutions is significantly higher than that of Portland cement paste. Otherwise, the alkali corrosion rate exhibits a high correlation with the concentration of the alkali solution [42]. Therefore, the alkali resistance of the current BF in a solution with alkalinity equal to that of the concrete material should be studied.

- (3) The alkali corrosion time of BF in the simulated alkali solution should be properly extended according to the specific concrete structure. As Figure 4 shows, the temperature of the raft foundation nearly returns to its normal temperature after 10 d; however, the dam needs 25 d to reach its initial temperature, which is considerably longer than the time required for the raft foundation. However, most of the alkali corrosion times in the aforementioned research were only a few hours and certainly not more than 7 d. Even in the case of accelerated alkali corrosion experiments at a higher temperatures and shorter times, the extent to which these test results reflect the actual conditions of BF in the concrete requires further study. Therefore, the alkali corrosion time of BF should be extended appropriately according to the actual expected working conditions.
- (4) The hydrophobicity of BF needs to be measured, and the moisture transport mechanism should be determined. The alkali resistance of the BF and the overall properties of the composites are improved by increasing its hydrophobicity. As previously mentioned, the long-term alkali resistance of BF needs to be improved. The existing methods for improving the hydrophobicity mainly include BF surface modification by plying gum, the addition of ZrO_2 into the BF [19], and the use of low-alkaline cement. However, many factors must be considered, such as the limited improvement, delaying alkali corrosion instead of stopping it, increasing the cost of the project, and the lack of supply, among others. However, through the determination of the zeta potential, Hu et al. [43–45] showed that although the BF was an inorganic material made from rock through melting and wire drawing, its surface was inert, and the elements on the surface of BF could form hydrogen bonds with hydrophilic polar groups. Meanwhile, the surface of BF contained many Si atoms, which would chemically react with the surrounding active groups under certain conditions. Therefore, the alkali corrosion reaction can readily occur. On the other hand, water is a transmission medium of various ions. If the hydrophobicity of BF is good, the alkaline corrosion ions cannot easily enter the fiber because of the lack of the transmission medium, and it is difficult to destroy the

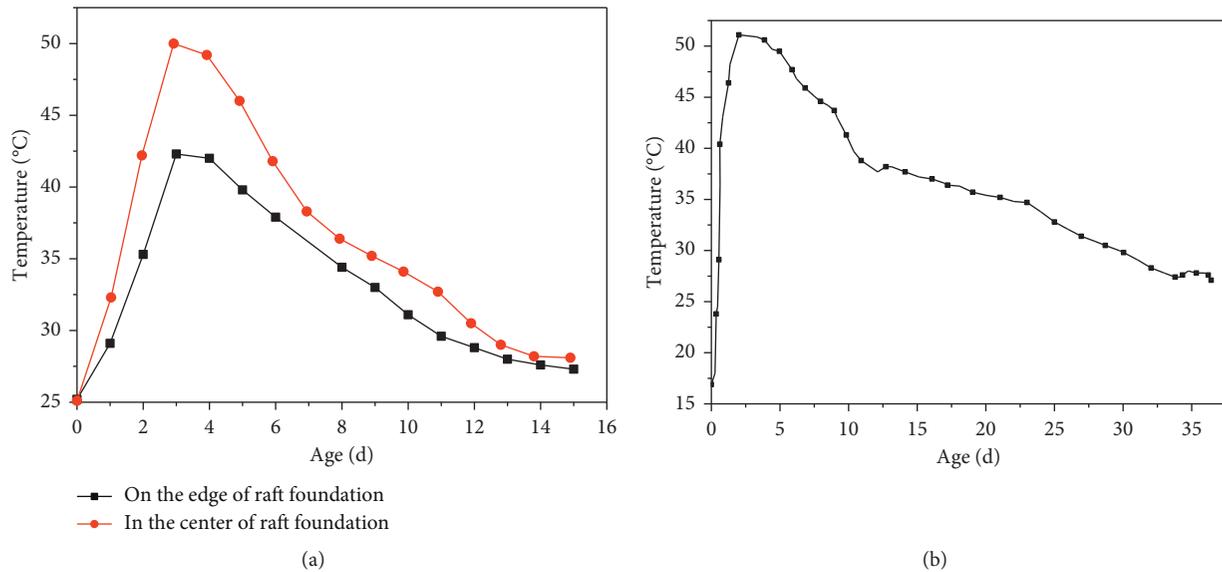


FIGURE 4: Curves showing the variation of temperature with increasing age of the concrete. (a) The measured values of the temperature field of the concrete at different points of a raft foundation and (b) the measured temperature field value of the concrete at the center of the base of an arch dam [46, 47].

BF. By contrast, BF can not only absorb the surrounding water used for the cement hydration reaction, which adversely affects the hardening of the concrete and the properties of the fiber/matrix interface, but also provide the carrier for the transmission of the alkali corrosion ions. Therefore, improvements in the hydrophobicity of BF and in the ability to block moisture are beneficial for improving the alkali resistance as well as the mechanical properties and durability of the BFRC. The hydrophobic and moisture transmission of BF has rarely been reported in depth in the literature. The next step should be to improve the alkali resistance of BF and the overall performance of the composite by measuring the hydrophobicity and elucidating the moisture transmission mechanism. From these two aspects of the BF and the concrete, through fiber surface modification and by adding mineral admixtures into the matrix, the dispersion of the BF in the matrix and the BF/matrix interfacial properties would be improved and the mechanical properties of the composite would be enhanced.

3. Static Mechanical Properties of BFRC

Similar to conventional concrete members, BFRC members have been subjected to various loads under different working conditions. Research on the static mechanical properties has also mainly focused on the strength, flexural toughness, and fracture mechanical properties, which are elaborated below.

3.1. Strength of BFRC. In recent years, researchers have studied the change rule for the mechanical properties of various concretes, including ordinary concrete, self-compacting concrete,

concrete with high mineral-admixture contents, shotcrete, and concrete-filled steel tubes. This work consisted of measuring the compressive, tensile, and flexural strengths of BFRC with different fiber contents under different conditions, such as different fiber ages and mineral admixtures. The fiber content has typically been on the order of $0.5\text{--}8.5\text{ kg/m}^3$, the investigated aging times have mostly been 3 d, 7 d, and 28 d, and the mineral admixtures have mainly included fly ash and silica fume. We will describe these below.

In 2008, Li et al. [48] studied the 28 d cubic compression, axial compression, splitting tensile, and flexural strengths of BF-reinforced self-compacting concrete (BFRSCC) (Figure 5) with a fiber content of $0.8\text{--}4.8\text{ kg/m}^3$, a length of 10–25 mm, and a diameter of $7\text{--}15\text{ }\mu\text{m}$ in accordance with CECS13:89. The results showed that with increasing fiber content, compared with that of plain self-compacting concrete (PSCC), the cubic compressive strength of the BFRSCC decreased by 3–10%. The overall trend of the axial compressive strength of BFRSCC first decreased and then increased before finally reaching strength slightly greater than that of PSCC. The splitting tensile strength gradually increased after an initial slight reduction, whereas the flexural strength decreased after initially slowly increasing. Both the tensile and flexural strengths showed peak values, where the maximum increase was 17% and 24%, respectively, and the corresponding optimal fiber content is 3.2 kg/m^3 . These results were attributed to the BF [48], which is soft and fine, forming a weak honeycomb-like or pore-like structure in the concrete and resulting in poor dispersion or a clustering phenomenon in the process of concrete mixing. These features reduced the density of the concrete and the cubic compressive strength. For the axial compressive strength, in addition to the aforementioned discussion, the increasing BF had a lateral restraint effect similar to that of stirrups, which improved the

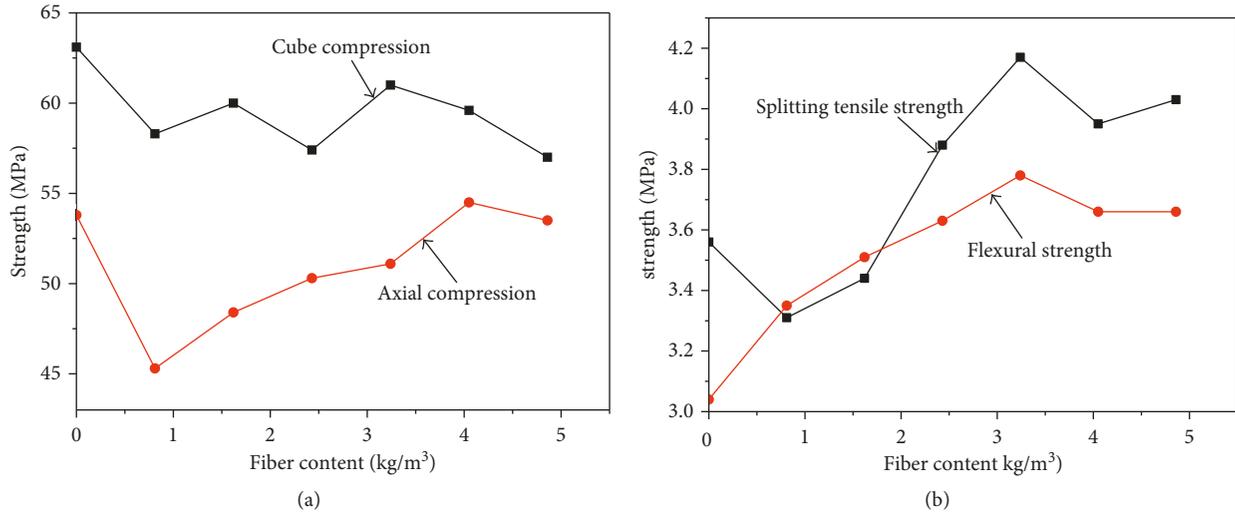


FIGURE 5: The effects of fiber content on (a) the cubic and axial compressive strengths and (b) the splitting tensile and flexural strengths of BFRSCC [48].

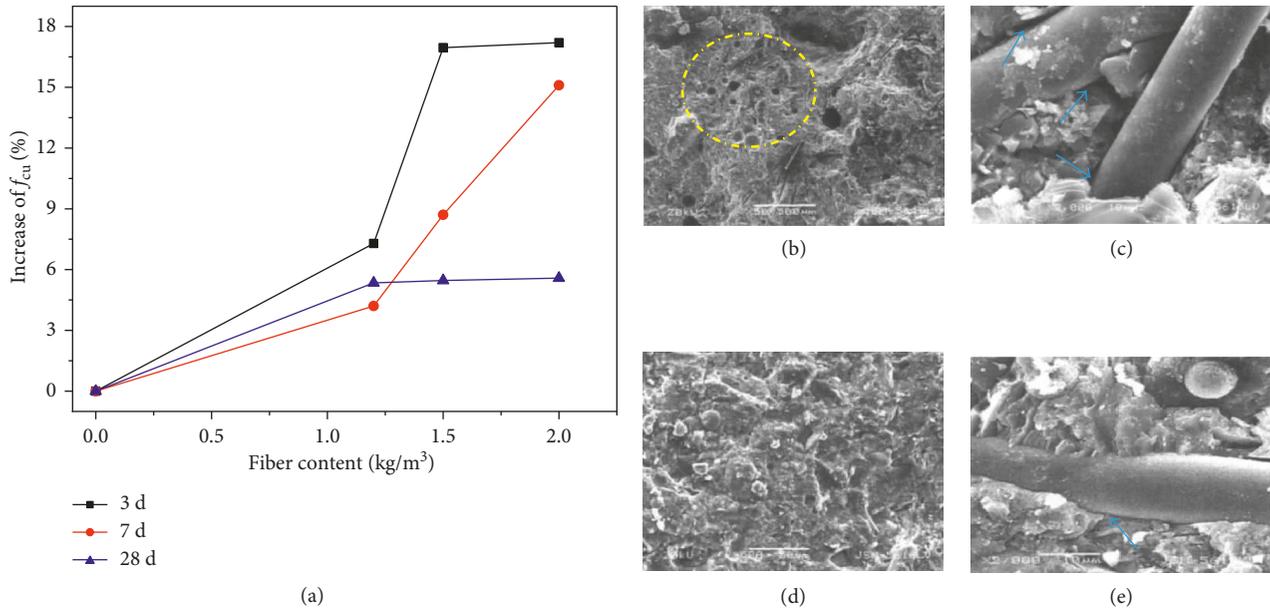


FIGURE 6: The effect of the pretreatment of BF on BFRSCC: (a) the change of the cubic compressive strength (f_{cu}) at different ages with the fiber content, (b) the section of matrix without pretreatment, (c) the interface between BF and matrix without pretreatment, (d) the section of matrix with pretreatment, and (e) the interface between BF and matrix with pretreatment [51].

compressive strength of the matrix. Under the influence of two plus-minus factors, the axial compressive strength exhibited a parabolic variation. The research concerning the axial compressive strength of the BFRC-filled steel tubular short columns, reported by Wang et al. [49] in 2013, also demonstrated this point. The splitting tensile and flexural strengths could be used as indexes to evaluate the tensile strength of the material. According to composite theory [50], the ultimate tensile strength of the BFRC was directly related to the ultimate tensile strength of the fiber and its content; otherwise, the tensile strength of BF is higher. Consequently, a reasonable amount of BF could improve the two mechanical

indexes without affecting the workability of the self-compacting concrete.

In 2009, by pretreating BF via wrapping up it with cement paste before mixing, Wu et al. [51] investigated the compressive strength of the BFRC standard cubic specimens with a fiber content of 1.2–2.0 kg/m³, a length of 12 mm, and a radius of 15 μ m according to the standard GB/T 50081-2002. The results showed that (Figure 6(a)) with increasing fiber content, the biggest growth of 28 d and early cubic compression strength (f_{cu}) of BFRC was about 5% and 17%, respectively. Compared with the results of Li et al. [48], the pretreatment had improved the compressive properties of

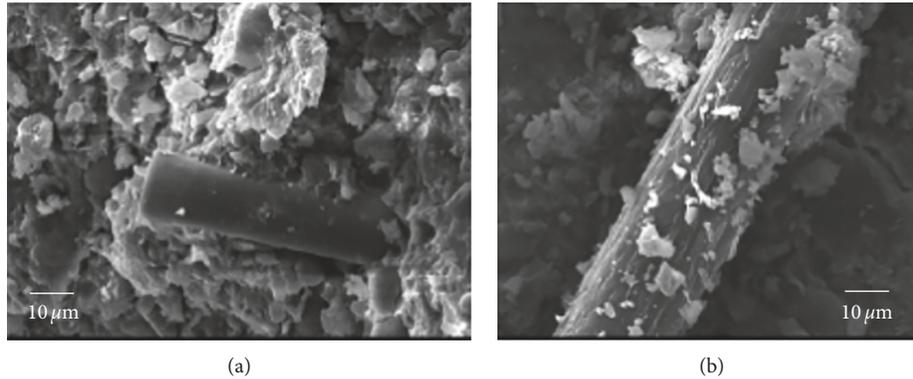


FIGURE 7: The micromorphology of the (a) BF and (b) PPF fibers in concrete [53].

BFRC to some extent. The reason was that the cement paste provided a lubricating effect between fibers and aggregates and made them fully contact with each other, thus effectively reducing the porosity of the matrix and enhancing the interfacial bond between fibers and matrix (Figures 6(b)–6(e)). In addition, the fibers wrapped with cement paste had better fluidity in the matrix, which increased its distribution uniformity.

In 2011, Ye et al. [52] studied the flexural tensile strength of high-strength BFRC with a relatively large amount of fly ash and silica fume with a fiber content of 8.4 kg/m^3 and a length of 6 mm, 18 mm, and 30 mm. The fiber was pretreated in three ways: direct shortcutting, plying gum, and twisting and plying gum. The results showed that compared with the PC, the maximum increase at 3 d, 7 d, and 28 d for the flexural tensile strength of BFRC was 20%, 27%, and 18%, respectively. The corresponding optimum fiber length and pretreatment method were 18 mm with direct shortcutting fiber. On the basis of the changing rate of the increase in strength with age, no apparent weakening of the fiber reinforcement with age was observed in the experiments, which might be related to the improvement in the alkali resistance.

In 2012, Luo and Bi [53] studied the influence of BF and hybrid fibers composed of BF and polypropylene fiber (PPF) on the cubic compressive strength of self-compacting concrete from the perspective of its pore structure. The BF contents were 1.3 kg/m^3 and 2.7 kg/m^3 , while the PPF content was $0.05\text{--}0.3 \text{ kg/m}^3$. In the case of concrete reinforced only by BF, the results suggested that the compressive strength was reduced compared with that of PSCC, similar to the results of a study by Li et al. [48]. This strength reduction was attributed to three factors. First, according to the four levels of pore size in the concrete proposed by Wu and Lian [54], the reduction of harmless or less harmful pores and the increase of harmful or more harmful pores in the BFRC would result in reduced density and strength. Second, from the perspective of micromorphology (Figure 7), BF was quite smooth compared to PPF. Thus, a very few hydration products would adhere to it, leading to weakening of the BF/matrix interface, which in turn diminished the effective advantages of the fiber properties. The third factor was the failure mode. Only cracks appeared during the

compressive failure of BFRC; no fragments were observed to burst apart. The failure mode of the BFRC was integrated, which suggested that the toughness of the specimen increased. For the hybrid fiber-reinforced self-compacting concrete, the 28 d strengths were improved by various degrees, and the greatest increase was approximately 38%. The corresponding contents of BF and PPF were 2.7 kg/m^3 and 0.1 kg/m^3 , respectively. The existence of PPF decreased the density and pore size, and the elasticity modulus and tensile strength of PPF were smaller than those of BF by an order of magnitude; the PPF thereby became a complementary support material to the BF, significantly increasing the strength.

In 2016, Zhou et al. [55] studied the splitting tensile and flexural strengths of BF-reinforced shotcrete under tunnel dry heat working conditions simulated using a stove and analyzed the structural mechanisms from the perspective of the anticrack functionality of the BF in the matrix. The ratio of raw materials was determined according to JGJ55-2000 and GB50086-2001. Their results suggested that the mechanical properties of the BF-reinforced shotcrete under dry heat conditions were significantly reduced compared with those measured under standard conditions. The existence of the BF could not appreciably improve the tensile and flexural strengths of the shotcrete, and the results even indicated a slight decrease in the mechanical properties at some fiber contents. The likely reasons for this behavior were related to the lower orientation coefficient of the three-dimensional, randomly distributed BF [50], the insufficient alkali resistance and dispersion of the BF used in the experiment, and the poor bond performance between the fiber and the matrix.

In 2016, based on the uniaxial compression test of BF-reinforced resin concrete cylinder and the theory of damage mechanics, Yu et al. [56] built the uniaxial compression constitutive model of the structure according to the generalized Hooke's law and the theory of Weibull strength distribution:

$$\sigma = 4.6 \times 10^4 \varepsilon \exp \left[- \left(\frac{\varepsilon}{0.006} \right)^{2.5} \right]. \quad (1)$$

The results indicated that the model agreed well with the experimental results, and the trend of change of model was

similar to that of plain concrete, but the strain during the rising section was obviously bigger than that of the latter [57]. This study made a theoretical contribution to the research on the mechanical properties of the material.

In short, research into the strength of the BFRC resulted in discrete or even opposite results because the strength was affected by the fiber characteristic parameters, fiber content, material properties of the matrix, preparation method, and the composite age, among other factors. However, the existence of BF in general had little effect on the compressive strength of the concrete but could nonetheless result in apparent improvements in the tensile and flexural strengths. The fiber content influenced the strength of the material, and an optimal content value existed. The adulteration of mineral admixtures and PPF was beneficial to the BF's enhancement of the concrete. On the basis of the aforementioned studies, further research can be conducted on the optimal mixture ratio and to complement the reinforcement mechanism from BF and other fibers with different properties, such as PPF, on the basis of different matrix materials and requirements.

3.2. Flexural Toughness and Fracture Mechanics. A few published works exist on the flexural toughness and fracture mechanics of BFRC. Scholars have mainly studied the influence of the characteristic parameters, such as the content and aspect ratio of the fiber, on the flexural toughness index, fracture toughness, and fracture energy. They have also discussed improvements in the toughness and fracture properties of the concrete as a result of the fiber. These results are illustrated and analyzed below.

He and Lu [58] and Ye et al. [52] reported on the flexure toughness of a B2010 beam in 2009 and 2011, respectively. The index used to measure the flexure toughness was the JSCEG552 standard proposed by the Japan Society of Civil Engineers. The flexure toughness of the BFRC was 5.6 times that of PC, as reported by He and Lu [58]. However, in the latter study, Ye et al. [52] noted that the BFRC, which was influenced by the fiber length, twisting treatment, and surface modification, exhibited a flexure toughness only 1.2–2.1 times of that of PC, as evaluated under different experimental conditions. Because the roughness of the fiber increased after the twisting treatment, which improved the bonding properties between the fiber and the matrix, the load-displacement curve of the concrete reinforced by twisted fiber was much flatter. The twisted fiber could substantially improve the toughness of the concrete. In consideration of the data in the latter report was much more sufficient, the results were closer to practical situations. Nonetheless, the presence of BF could clearly improve the flexure toughness of concrete.

In 2016, according to ASTM E647-11 and RILEM three-point bending test method, Xue et al. [59] studied the influence of the BF content and aspect ratio on three performance parameters: the fracture energy, fracture toughness, and the ductility index, which defined the fracture mechanics properties of concrete, and thoroughly analyzed the impact mechanism. The BF content in their study was approximately

6.6–40 kg/m³, the diameter was 15 μm, and the length was 5–25 mm. Their results suggested the following:

- (1) There were three stages during the occurrence and development of cracks in BFRC: (i) the no-cracks expanding stage when the fiber and concrete worked together; (ii) the crack stable growth stage, where the bridge stress of the fiber had delayed effects; and (iii) the crack unstable growth stage after the net stress of the crack tip reached the ultimate stress.
- (2) The presence of the BF could improve the fracture mechanics of the concrete to some extent. The amplifications were 37% in the fracture energy, 44% in the fracture toughness, and 19% in the ductility index. The variation tendencies of all of the three fracture mechanical parameters first increased and then decreased with increasing fiber content and increasing aspect ratio. Thus, a corresponding BF optimal content or aspect ratio existed.
- (3) The mechanism by which the BF influenced the fracture mechanics of the concrete was as follows:
 - (i) The BF filament is too soft, fine, and smooth to induce surface modification [6] and anchorage, and its tensile strength is high. Therefore, the interfacial bonding stress might be less than the tensile strength of the fiber, and the main cause of failure was that the fibers being withdrawn during the process of fracture failure. However, the nonmain crack resistance increased when the cracks propagate and the fracture performance was improved by benefiting from the interfacial debonding, frictional slip, and obliquity effect. However, the remaining pores would accelerate the unstable propagation of cracks as the composite reached its ultimate strength.

On the basis of the aforementioned research, one conclusion was that the BF would substantially improve the toughness and fracture mechanics of the concrete if the mixing and characteristic parameters of the fiber were properly selected.

3.3. Analysis and Prospects. After organizing and summarizing the studies regarding the strength, toughness, and fracture mechanics of the BFRC, we identify the following issues that require further research:

- (1) On the basis of the pullout test of a single (or single-bundle) BF with different distributions and orientations in the concrete, the coupling among the tensile strength, fiber/matrix interfacial bonding strength, and the lateral shear strength of the fiber as well as the optimal distribution of the fiber corresponding to different types of characteristic parameters can be determined. When the orientation of BF is consistent with the pullout force, the fiber will be easily pulled out. By contrast, if the included angle between the fiber and the pullout force is too large, lateral shear failure will most likely occur for the

fiber. In both circumstances, the tensile strength of the fiber cannot be efficiently utilized. Thus, if the coupling among them could be realized and an optimal orientation distribution of diverse types of fibers could be obtained, the mechanical properties (e.g., the tensile, flexure, and fracture performance) of the BFRC can be significantly improved.

- (2) The formula concerning the critical content and aspect ratio of the BF in concrete can be established with respect to the bonding properties between the BF and the concrete and the random distribution characteristics of the fiber in the matrix. In the current research body, only the influence of the fiber content and aspect ratio on the mechanical properties is reported, whereas experimental studies and theoretical analyses of the critical content and aspect ratio remain obscured. However, according to the theory of the compound function between a fiber and a concrete [50], the ultimate tensile strength could only be significantly improved when the fiber content was larger than the critical value. The relationship between the actual aspect ratio and the critical aspect ratio of the fiber directly influenced the failure mode and the realization of fiber enhancement. Therefore, additional research on this aspect is needed.
- (3) The mechanical model of BFRC needs an in-depth study in order to fully reveal its mechanical behavior mechanism. Based on the above analysis, it is found that the number of model research about BFRC is very limited in China. Compared with the uniaxial compression constitutive model of high-strength BFRC proposed by Ayub et al. [60], these models still have some defects such as the inadequate reflection of the fiber content and the single expression of stress-strain full process, and they need further modifications and perfections. In addition, the static mechanics model research of BFRC such as shear and bending mechanics is still rare. Therefore, it will be an important area for future research.

4. Conclusion

In summary, the studies reported in China in this century described the alkali resistance of fibers under different alkali corrosion environments and pretreatment methods, and the static mechanical properties, such as the strength and toughness, of the BFRC under different characteristic parameters and content. The main results were illustrated as follows: the composition and temperature strongly influenced the alkali resistance of the BF, whereas the pretreatment had limited effects; the BF had almost no effect on the compressive strength but could significantly improve the tensile and flexural strengths; in addition, the fiber content could notably influence the strength.

Hereby, we propose the following six research topics related to alkali resistance and static mechanical properties of three-dimensional, randomly distributed BFRC:

- (1) The alkali resistance and adaptability in the concrete with BF under the conditions of dynamic alkali corrosion temperature, lower concentration of alkali, and longer alkali corrosion times should be measured and investigated. In addition, its mechanism of influence on the mechanical properties of the BFRC should be investigated.
- (2) On the basis of the determination of the hydrophobicity and moisture transmission mechanism of the fiber, the alkali resistance of BF and the integral performance of composites can be improved via the BF's hydrophobicity and moisture transmission.
- (3) On the basis of the pullout test of a single (or single-bundle) BF with different distributions and orientations in the concrete, the optimal orientation of the BF with different characteristic parameters should be investigated to achieve the maximum enhancement to the matrix.
- (4) A formula for the critical content and aspect ratio for various kinds of BFs in concrete should be established, and the mechanism of influence of the BF with different contents and aspect ratios on the mechanical properties of the matrix (e.g., tensile, flexure, and fracture performance) should be explored, and the aforementioned properties should be optimized.
- (5) With the objective of varying the material characteristics and applications of the matrix, the optimal mixture ratio and the complementary mechanism between the BF and other types of fibers with different properties, such as PPF, in the concrete should be studied.
- (6) From the perspective of BF and the concrete, the dispersion of the BF and BF/matrix interfacial properties should be improved through surface modification of the fiber and the addition of mineral admixtures to the matrix, thereby improving the mechanical properties of the composites.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Grant no. 51578140).

References

- [1] Y. Gong, R. X. Shen, and H. Q. Li, *Application of Dura Fiber in Civil Engineering*, China Machine Press, Beijing, China, 2002, in Chinese.
- [2] L. H. Xu, D. T. Xia, G. Z. Xia, and Y. Chi, "Effect of steel fiber and polypropylene fiber on the strength of high strength concrete," *Journal of Wuhan University of Technology*, vol. 29, no. 4, pp. 58–60, 2007.
- [3] S. L. Xu and H. D. Li, "A review on the development of research and application of ultra high toughness cementitious

- composites," *China Civil Engineering Journal*, vol. 41, no. 6, pp. 45–60, 2008.
- [4] J. Y. Sun, "Frost resistance characteristics of fiber concrete," *Journal of Building Materials*, vol. 16, no. 3, pp. 437–440, 2013.
- [5] X. Q. Hu, Y. F. Luo, and T. N. Shen, "Basalt continuous fiber and its reinforcing composite material," *Hi-Tech Fiber and Application*, vol. 27, no. 2, pp. 1–11, 2002.
- [6] G. J. Wang, D. K. Shang, L. N. Hu, K. L. Zhang, Z. H. Guo, and Y. J. Guo, "Investigation of modification of basalt fibers and preparation of ecomposites thereof," *Acta Materiae Compositae Sinica*, vol. 21, no. 1, pp. 38–44, 2004.
- [7] L. A. Shi, H. Y. Ma, and Z. D. Rong, "Influence of basalt fiber and its geotextile on mechanical performance of ultra-high performance cement composites," *Journal of Nanjing University of Aeronautics and Astronautics*, vol. 44, no. 3, pp. 415–419, 2012.
- [8] D. Zhang, Q. Xu, and Y. Guo, "Experiments on strength and shrinkage of expansive soil with basalt fiber reinforcement," *Journal of Southeast University*, vol. 42, no. 5, pp. 975–980, 2012.
- [9] L. J. Ouyang, B. Ding, Z. D. Lu, and J. T. Yu, "Experimental study on seismic performance of short columns strengthened with BFRP and CFRP," *Journal of Tongji University*, vol. 41, no. 2, pp. 166–172, 2013.
- [10] J. F. Mao, W. G. Dong, and S. Z. Cong, "Characteristics and application prospect of basalt fiber," *Technical Textiles*, vol. 10, pp. 38–40, 2007.
- [11] R. Yang and Z. Wang, "Research on physical and mechanical properties of basalt fiber reinforced concrete," *Yangtze River*, vol. 46, no. 13, pp. 78–81, 2015.
- [12] L. Zhao, "The influences of basalt fiber on mechanical properties of cement-based materials," *China Concrete and Cement Products*, vol. 9, pp. 46–48, 2012.
- [13] Y. C. Zhang, Q. N. Li, and C. Z. Fang, "Study of the mechanical properties and durability of fiber reinforced concrete based on meso analysis," *Concrete*, vol. 8, pp. 48–50, 2016.
- [14] D. X. Hao, "The progress of basalt fiber and its product technology abroad," *China Building Materials Science and Technology*, vol. 3, pp. 84–85, 1990.
- [15] Y. H. Gu, "Alkali resistant mineral fiber," *Fiber Glass*, vol. 4, pp. 32–42, 1978.
- [16] L. Wang, Y. Chen, and Z. W. Li, "Properties of continuous basalt fiber and composites," *Fiber Reinforced Plastics/Composites*, vol. 6, pp. 22–24, 2000.
- [17] Y. Chen, L. Wang, and Z. W. Li, "Properties and application of basalt fiber," *New Building Materials*, vol. 8, pp. 28–31, 2000.
- [18] J. Sim, C. Park, and D. Y. Moon, "Characteristics of basalt fiber as a strengthening material for concrete structures," *Composites Part B: Engineering*, vol. 36, no. 6–7, pp. 504–512, 2005.
- [19] Y. V. Lipatov, S. I. Gutnikov, M. S. Manylov, E. S. Zhukovskaya, and B. I. Lazoryak, "High alkali-resistant basalt fiber for reinforcing concrete," *Materials and Design*, vol. 73, pp. 60–66, 2015.
- [20] T. M. Borhan, "Properties of glass concrete reinforced with short basalt fibre," *Materials and Design*, vol. 42, pp. 265–271, 2012.
- [21] T. M. Borhan and C. G. Bailey, "Modelling basalt fibre reinforced glass concrete slabs at ambient and elevated temperatures," *Materials and Structures*, vol. 47, no. 6, pp. 999–1009, 2014.
- [22] T. M. Borhan and C. G. Bailey, "Structural behaviour of basalt fibre reinforced glass concrete slabs," *Materials and Structures*, vol. 47, no. 1–2, pp. 77–87, 2014.
- [23] M. Sinica, G. A. Sezeman, D. Mikulskis, M. Kligys, and V. Česnauskas, "Impact of complex additive consisting of continuous basalt fibres and SiO₂ microdust on strength and heat resistance properties of autoclaved aerated concrete," *Construction and Building Materials*, vol. 50, pp. 718–726, 2014.
- [24] T. Ayub, N. Shafiq, and M. F. Nuruddin, "Effect of chopped basalt fibers on the mechanical properties and microstructure of high performance fiber reinforced concrete," *Advances in Materials Science and Engineering*, vol. 2014, Article ID 587686, 14 pages, 2014.
- [25] N. Kabay, "Abrasion resistance and fracture energy of concretes with basalt fiber," *Construction and Building Materials*, vol. 50, pp. 95–101, 2014.
- [26] Nanjing Fiberglass Research and Design Institute, "Melt mineral wool slag with containing titania," *Fiberglass*, vol. 1, p. 6, 1978.
- [27] R. X. Shen, "Improving durability of glass fiber in cement-base materials," *Journal of the Chinese Ceramic Society*, vol. 6, no. 3, pp. 199–213, 1978.
- [28] S. Q. Du, "Prospects for development and applied range of basalt fiber," *Fiberglass*, vol. 4, p. 49, 1980.
- [29] X. W. Zhao, "Basalt fiber reinforced concrete," *Journal of Water Resources and Water Engineering*, vol. 3, p. 75, 1990.
- [30] X. Q. Hu and S. N. Hu, "The applications of the CBF in war industry & civil fields," *Hi-Tech Fiber and Application*, vol. 30, no. 6, pp. 7–13, 2005.
- [31] D. Q. Ye, "Continuous basalt fiber-new materials in twenty-first Century," *Building Materials Industry Information*, vol. 6, p. 5, 2002.
- [32] B. P. Wang and W. Zhang, "Properties and applications of basalt fiber," *Research and Application of Building Materials*, vol. 4, pp. 17–18, 2002.
- [33] GB/T 23265-2009, *Chopped Basalt Fiber for Cement, Cement Mortar and Concrete*, Standards Press of China, Beijing, China, 2009.
- [34] JCT 572-94, *Alkali-Resistant Glass Fiber Twistless Roving*, Standards Press of China, Beijing, China, 1978.
- [35] B. Wei, H. L. Cao, and S. H. Song, "Tensile behavior contrast of basalt and glass fibers after chemical treatment," *Material Design*, vol. 31, no. 9, pp. 4244–4250, 2010.
- [36] F. Z. Li, G. C. Li, H. M. Wang, and Q. Tong, "Effect of acid/alkali corrosion on properties of basalt fiber yarn," *Materials Review B*, vol. 29, no. 1, pp. 110–113, 2015.
- [37] M. C. Wang, Z. G. Zhang, Z. J. Sun, and M. Li, "Corrosion resistance characteristic of continuous basalt fiber and its reinforcing composites," *Journal of Beijing University of Aeronautics and Astronautics*, vol. 32, no. 10, pp. 1255–1258, 2006.
- [38] W. J. Huo, Z. G. Zhang, M. C. Wang, M. Li, and Z. J. Sun, "Experimental study on acid and alkali resistance of basalt fiber used for composites," *Acta Materiae Compositae Sinica*, vol. 24, no. 6, pp. 77–82, 2007.
- [39] K. J. Huang and M. Deng, "Stability of basalt fibers in alkaline solution and its effect on the mechanical property of concrete," *Acta Materiae Compositae Sinica*, vol. 27, no. 1, pp. 150–154, 2010.
- [40] X. Wu, W. L. Chen, Z. Y. Wang, and C. F. Yu, "Experimental study on the properties of basalt fiber yarn," *Journal of Zhejiang Sci-Tech University*, vol. 29, no. 5, pp. 660–663, 2012.
- [41] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, China Electric Power Press, Beijing, China, 2008, in Chinese.
- [42] Z. Li, T. L. Xiao, Q. Y. Pan, J. M. Cheng, and S. G. Zhao, "Corrosion behaviour and mechanism of basalt fibres in

- acidic and alkaline environments,” *Corrosion Science*, vol. 110, pp. 15–22, 2016.
- [43] M. F. Fang and H. Huang, “Study and application of wood plastic composites,” *Modern Agricultural Science and Technology*, vol. 3, pp. 8–14, 2009.
- [44] L. N. Hu, D. K. Shang, S. J. Li, W. H. Chen, and B. J. Song, “Study on the interfacial functionary mechanism of plant fiber/basalt fiber composite material,” *Polymer Materials Science and Engineering*, vol. 20, no. 6, pp. 29–32, 2004.
- [45] S. Nachtigall, A. Felix, and R. Mauler, “Blend compatibilizers based on silane- and maleic anhydride-modified polyolefins,” *Journal of Applied Polymer Science*, vol. 88, no. 10, pp. 2492–2498, 2003.
- [46] J. Wang, S. Yan, and J. L. Wang, “Numerical simulation and real-time survey of temperature fields of mass concrete in raft-foundation,” *Journal of Liaoning Technical University*, vol. 34, no. 3, pp. 364–368, 2015.
- [47] W. M. He and J. M. Guo, “Monitoring and measurement of core temperature of mass concrete,” *Journal of Railway Engineering Society*, vol. 6, pp. 64–67, 2011.
- [48] R. Li, Z. Bi, Y. Wang, and H. Y. Liu, “Experimental study on mechanical properties of short basalt fiber self-compacting concrete,” *China Concrete and Cement Products*, vol. 2, pp. 48–50, 2008.
- [49] H. L. Wang, H. Li, X. L. Yang, Q. C. Ren, and P. Dong, “Experimental research on basalt fibre reinforced concrete filled steel tubular short columns subjected to axial compression load,” *Building Structure*, vol. 43, no. 22, pp. 22–25, 2013.
- [50] J. Z. Xu, *Technology and Application of Fiber Reinforced Concrete*, China Architecture and Building Press, Beijing, China, 2003, in Chinese.
- [51] Z. X. Wu, H. Q. Yuan, Z. A. Lu, and X. C. Fan, “Experimental research on mechanical properties of basalt fiber reinforced concrete,” *Concrete*, vol. 9, pp. 67–78, 2009.
- [52] B. T. Ye, J. Y. Jiang, W. Sun, C. H. Wang, and J. Hu, “Experimental study on reinforcing HSC with large volume mineral admixtures basalt fibers,” *Journal of Southeast University*, vol. 41, no. 3, pp. 611–615, 2011.
- [53] B. B. Luo and Q. W. Bi, “Experimental study on the influence of pore structure of hybrid fibers self-compacting concrete on compressive strength,” *Bulletin of the Chinese Ceramic Society*, vol. 31, no. 3, pp. 626–630, 2012.
- [54] Z. W. Wu and H. Z. Lian, *High Performance Concrete*, China Railway Press, Beijing, China, 1999, in Chinese.
- [55] P. Zhou, Z. J. Wang, Y. Yang, and X. F. Ji, “Experimental study of the performance of basalt fiber shotcrete under heat damage,” *Journal of Civil, Architectural and Environmental Engineering*, vol. 38, no. 1, pp. 69–76, 2016.
- [56] Y. H. Yu, R. F. Wu, Y. M. Chen, and P. Xu, “Uniaxial compression constitutive model of basalt fiber nesin concrete,” *Concrete*, vol. 9, pp. 69–71, 2016.
- [57] GB 50010-2010, *Code for Design of Concrete Structures*, China Architecture and Building Press, Beijing, China, 2010.
- [58] D. Q. He and Z. A. Lu, “Experimental study on mechanical properties of chopped basalt fiber reinforced concrete,” *Journal of Henan University*, vol. 39, no. 3, pp. 320–322, 2009.
- [59] Q. C. Xue, J. C. Zhang, J. He, and T. J. Ramze, “Experimental study of fracture properties for basalt-fiber-reinforced concrete,” *Journal of Harbin Engineering University*, vol. 37, no. 8, pp. 1027–1033, 2016.
- [60] T. Ayub, N. Shafiq, and S. U. Khan, “Compressive stress-strain behavior of HSFRC reinforced with basalt fibers,” *Journal of Materials in Civil Engineering*, vol. 28, no. 4, article 06015014, 2016.



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