ISSN 2959-6157

Study on Mechanical Properties of Basalt Fiber and its Composite Materials

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Abstract:

With the development of civil engineering industry, the use of new composite materials has become an inevitable trend. This paper mainly focuses on the mechanical properties and development status of Basalt Fiber (BF) and its fiber composites which is called Basalt Fiber Reinforced Polymer (BFRP). The raw material of BFRP, the basalt ore and the preparation of blast furnace are discussed. Then, the preparation method of BFRP is introduced. In the process of research, it is found that when the preparation of BFRP is completed, the types of BFRP can be roughly divided into mixed reinforcement type and basic profile type. Subsequently, the factors affecting the mechanical properties of blast furnace are studied, which are mainly divided into interface modification and interface aging. In the aspect of interface modification, four modification methods such as acid-base etching modification, plasma surface treatment, silane coupling agent treatment and nanoparticle modification are introduced in detail. Finally, comparing BF with carbon fiber (CF), polyester fiber (PF) and glass fiber (GF), it is found that BF has better plasticity, toughness, good electrical insulation and low thermal conductivity. However, there are still many difficulties to be solved in the production, preparation, modification and application of BF and BFRP.

Keywords: Basalt Fiber, mechanical properties, interface modification, interface aging.

1. Introduction

In recent years, all countries in the world are faced with the problems of environmental pollution, resource shortage and ecological degradation. Moreover, with the continuous development of construction technology, the demands for structures and materials in complex projects is also increasing [1]. Therefore, under the concept of sustainable development and the needs of structural engineering, the research and development of new green high-performance environmental protection materials has become an inevitable trend in the current era. The fiber reinforced composite has attracted much attention due to its unique mechanical properties, good durability and environmental friendliness.

BFRP is produced by the composite of BF and other materials. For BF, as early as the 1990s, China has begun to study it. BF is made from the natural volcanic rock. The rock needs melting fluid at high temperature through spinning and drawing process of fiber. Then it shows excellent performance in tensile, compressive, sound insulation and other aspects. In recent years, with the continuous development of production technology, China's BF output has accounted for half of the world's total output by 2020 [2]. In the composite process of BF and other materials, the excellent mechanical properties of different materials such as corrosion resistance, high temperature resistance, sound insulation and heat insulation can be superimposed. Studies have shown that BFRP has better mechanical properties than other fiber composites in some aspects. For example, the interlaminar shear strength of BFRP is 11% higher than that of glass fiber composite, and BFRP has higher bending strength and better resistance to impact damage [3]. In addition, BFRP also has the characteristics of low cost and easy recovery. As a result, many studies and investigations have been carried out around the world on the preparation, improvement and application of BFRP. Nowadays, BFRP has been widely used in civil engineering, aerospace and many other fields. In the aerospace field, BFRP can be used to make aircraft structural parts and missile casings, not only to reduce weight, but also to improve strength and heat resistance. In the field of civil engineering, BFRP can be used to produce high-strength and high-durability building materials, which can greatly improve the seismic performance and service life of buildings [4]. The main content of this paper is to introduce the preparation method of BFRP and summarize the factors affecting the mechanical properties of BFRP. Then, compared with other fiber composites, the advantages and disadvantages of BFRP and BF will be shown in this paper. Finally, combined with the application of BFRP in the field of civil engineering, the future development of BFRP is prospected.

2. Preparation of BFRP

2.1 The Production of BF

As the raw material of BF production, basalt is an extrusive rock and it is most widely distributed among igneous rocks, accounting for more than 90% of all igneous rocks [5]. Basalt is mainly distributed in deep ocean ridges, seamount islands, continental margins and continental interiors. The mineral composition of basalt is an important factor affecting the production and mechanical properties of BF products. However, nowadays, there is a lack of detailed data analysis and summary of the mineral composition of basalt in different regions. Moreover, the mineral composition of basalt in different regions is quite different, so there is still a big gap between the production of BF and the stability of quality.

The production of basalt fiber is mainly divided into two methods: crucible method and pool kiln method. The crucible method is used for secondary spinning, and the manufacturing process of this method is flexible and the equipment cost is low. While the disadvantage is that the production capacity is limited and cannot be used for large-scale mass production. Compared with the crucible method, the pool kiln method uses a single filament, its production process is simple, less energy consumption, and there is a high yield. However, due to the high temperature, the service life of the leakage plate will become shorter and easily deformed. As a result, the cost of basalt production will be greatly increased. In addition, the tank kiln method has low production efficiency and low product performance.

2.2 The Preparation of BFRP

The preparation methods of BFRP can be divided into two kinds: direct blending method and impregnation fusion method. Direct blending method is to blend basalt fibers into various materials for mixing and curing, and then weave them into various shapes and then mix and bond with other materials. However, when BF is directly mixed with other materials, it often appears that the bond with other materials is not tight. Compared with the direct blending method, the impregnation fusion method is slightly more complicated. At first, the basalt fiber is added to the impregnation device, and then the double screw extruder is used to melt and mix the materials into the mold. The high-performance BFRP will be obtained after traction, cooling, water removal, and granulating. The process of the two methods is shown in Fig. 1 and Fig. 2 [2].

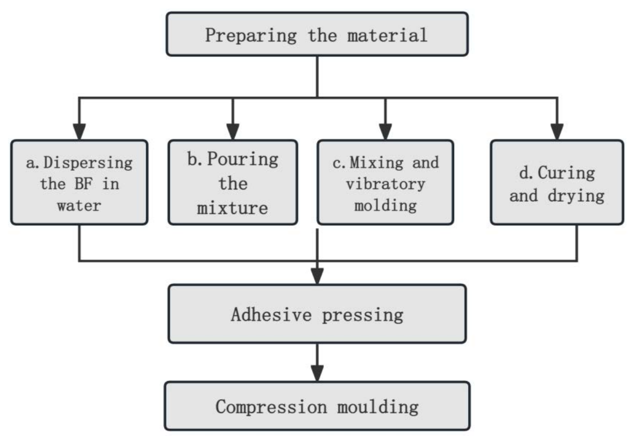

Fig.1 Direct blending process flow [2]

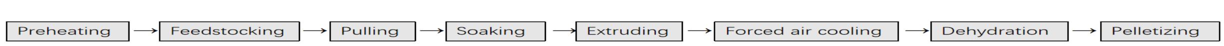

Fig.2 Impregnation fusion production process [2]

2.3 Product Types of BFRP

According to the product form, BFRP products can be divided into mixed reinforcement class and basic profile class. Mixed reinforcement products are mainly prepared by mixing chopped basalt fiber with gypsum, asphalt, concrete, soil, etc. Such products are widely used in building gypsum, filling road construction, reducing high-temperature rutting and road engineering construction. They can also reduce the probability of slope erosion and soil disintegration, so that the safety of construction can be significantly improved. The basic profiles made of basalt fiber and resin materials have high fracture toughness, tensile and bending properties. It can also greatly improve durability and corrosion resistance. Such materials can be processed into materials of various shapes, such as BFRP pipe segments and anchor rods [2].

3. Factors Affecting the Mechanical Properties of BFRP

3.1 Effects of Interface Modification

For BFRP, the degree of interface bonding is an important factor to determine its mechanical properties, especially for interlaminar shear, fracture and other properties. If BF and epoxy resin show weak interfacial compatibility, the interfacial junction will become a stress concentration point. Then the structural defects will reduce the ability of various mechanical properties of the material. The mechanical properties of BF and BRFP can be improved by interface modification. At present, the main methods of interface modification include acid-base etching modification, plasma surface treatment, silane coupling agent treatment and nanoparticle modification.

3.1.1 Acid-based etching modification

Acid-base etching modification is to soak the fiber in an acidic or alkaline solution, so that it reacts chemically with some components in the solution. Then it will form a groove on the surface of the fiber, so that the specific surface area of the fiber is increased. It is found through research that BF will be delamination peeling after acid treatment, which indicates that acid will erode BF from the outside in. However, alkali will erode BF from the inside and outside at the same time [6]. In addition, Manikandan et al. [7] compared the effects of sodium hydroxide and sulfuric acid on BFRP and found that acid-base treatment can increase the adhesion between basalt fiber and resin by increasing the rough surface of BF [8]. In general, the use of acid-base etching has the advantages of simple operation and low cost, but its modification effect is limited. When the concentration of acid and base is too high, the mechanical strength of BFRP will decrease.

3.1.2 Plasma surface treatment

Plasma modification is a method that uses high-energy neutral, ion and free electron active substances to bombard the surface of the material and open the chemical bond on the surface of the material. As a result, it can generate free radicals, and even break and decompose the polymer chain segment, to improve the adhesion of the fiber. Sun [9] treated BF with low temperature air plasma and changed the discharge power under the condition of constant pressure and discharge time. It was found that when the discharge power increased, the dynamic and static friction coefficient would increase, while the contact angle would decrease. Finally, the infiltrability of the fiber surface would increase. The cost of this method is high and the steps are complex, so it is not suitable for large-scale production.

3.1.3 Silane coupling agent treatment

The silane coupling agent treatment is affected by the type of silane coupling agent and the degree of hydrolysis. At present, many coupling agents can improve the mechanical properties of BF.In view of the limited research and limited data, it is not possible to determine which coupling agent is the best choice specifically for basalt fiber modification, which makes the coupling agent treatment will be severely limited.

3.1.4 Nanoparticle modification

Because the nano-particles have large surface activity and are nano-sized particles, they can be attached to the surface of basalt fiber through physical or chemical interaction to improve the bonding property between the matrix and basalt fiber. The experimental results show that the mechanical properties of BF will be improved to some extent when the content of nano-filler is increased. For example, when the content of Al2O3 nano-filler is increased from 0.2% to 0.6%, the tensile strength of BF can be increased by 35% [3]. This indicates that nanomaterials can improve the bonding strength between matrix and fiber in fiber composites.

3.1.5 Other modification methods

In addition to the above four modification methods, common fiber modification methods include rare earth modification, surface coating treatment, etc.. The advantages and disadvantages of each modification method are shown in Table 1 [10].

Table 1. The advantages and disadvantages of interface modification [10]

The method	Advantage	Disadvantage
Acid-base etching modification	Low cost	Much damage and will pollute the environment
Nanoparticle modification	No damage	The distribution of nano materials is uneven
Silane coupling agent treatment	No damage	Proportions are hard to control
Plasma surface treatment	Environmental and little damage	Not cost-efficient
Rare earth modification	Simple process and good effect	The rare earth is a non-renewable resource
Surface coating treatment	No damage	Easy uneven coating

3.2 Effect of Interface Aging (Temperature Effect)

In the process of using BFRP, the interface between the fiber and the matrix will be aging due to the influence of environmental factors such as light and heat, temperature and so on, resulting in a decline in mechanical properties. In addition, the fatigue life of basalt fiber composites decreases significantly with the increase of temperature. The effect of temperature on fatigue life of BFRP is emphasized here.

In order to study the influence of temperature on fatigue properties of BFRP, Zhao et al. [11] conducted fatigue tests at different temperatures. They first performed static tensile tests at different temperatures to obtain the tensile strength (σ_m) at each temperature. Then they carried out experiments with stresses of 75% σ_m, 70% σ_m, 65% σ_m and 60% σ_m at room temperature, 50℃ and 70℃ respectively. Because the temperature change of the specimen itself can be ignored when the loading frequency is between 0.1Hz and 25Hz, the loading frequency of 10Hz is selected. In the test, BFRP of the same size was subjected to more than five fatigue tests at each temperature, and after removing useless data, the results were averaged, as shown in Table 2. It can be seen from Table 2 that, when the stress level decreases, the number of cycles increases significantly. When the stress is the same, the fatigue life of BFRP decreases with the increase of temperature.

Table 2. Fatigue lives of BFRP plates under different stress levels at RT, 50 ℃ and 70 ℃ [11]

The stress level/%	RT	50℃	70℃
	Mean fatigue life N	Mean fatigue life N	Mean fatigue life N
75	6052	2840	492
70	18633	7779	4046
65	91556	66733	34336
60	403533	319676	237495

*Note: RT stands for room temperature and N is the number of cycles per unit of fatigue life.

4. Advantages and Disadvantages of BFRP

4.1 The Advantages of BF and BFRP

BF has many advantages over CF and GF in terms of performance. In terms of mechanical properties, BF has higher tensile strength, which can ensure that the product is more stable and durable. Compared with GF, BF has a larger elastic modulus and a stronger ability to resist elastic deformation. In addition, the ultimate productivity of BF is also greater than that of the other two fiber. Therefore, BF can better withstand the deformation of tensile fracture, and has better shaping and toughness. Other mechanical properties are shown in Table 3 [12]. BF also has great advantages over other fibers in terms of fiber performance. As shown in Table 4, BF has a wider operating temperature range, good electrical insulation and low thermal conductivity [13].

Table 3. Properties of basalt, carbon and glass fibre [12]

Property	BF	CF	GF
Diameter(μm)	15	7	13
Density (g/cm^3)	1.85-2.75	1.76	2.68
Tensile strength (Mpa)	2600-4840	>3000	1500
Elastic modulus (Gpa)	80-115	200	71
Ultimate elongation (%)	2.4-3.15	1.5	2.5
Melting point (℃)	1400-1450	>3000	860

Table 4. Performance indexes of fibers [13]

Fibre type	Temperature interval (℃)	Heat conductivity coefficient ([W·(m·K)-1])	Electric conductivity (Ω·m)
BF	-260~700	0031~0.038	1×1012
GF	-60~450	0.034~0.040	1×1011
CF	-50~350	5.000~185.000	2×105
PF	-10~160	0.240	1×1021

BF also has good economic benefits. For example, CF sells for up to $30 per kilogram, while BF costs only about $3. In addition, BF will not produce waste liquid, waste water and exhaust gas in the production process, so it will hardly cause harm to the environment and human body, and it can also be naturally degraded after being used.

In summary, compared with GF, BF has better mechanical properties, temperature resistance and mechanical properties phenotype. Compared with CF, BF not only has better temperature resistance, but also costs much less than CF. In addition, BF also has very good green and environmental protection performance. Taking various factors into consideration, the cost performance of BF and BFRP has exceeded that of GF commonly used in the market, and it is also a better choice compared with CF in many aspects [14].

4.2 The Disadvantages of BF and BFRP

4.2.1 Production problems of BF

Because the basalt ore composition in various regions is different, and now the research data on the mechanical properties of basalt are relatively lacking, so when the same production process is basically used in the production process, some basalt cannot be fully melted. Moreover, Zhang et al. [15] found that not every kind of basalt ore can be used as BF production raw material through the study of basalt in Guizhou and Sichuan.

In addition to the problem of raw materials, the production management efficiency of BF is also low. Taking 13 μm nanofibers as an example, the average daily production of 200 holes of leaky plate is only about 150 kg, only reaching 60% of the production capacity. In contrast, the average daily production of non-alkali glass fiber can reach 250 kg [16].

4.2.2 Production problems of BFRP

In the direct blending method, because the interface of BF is smooth and not easy to chemically react with other materials, BF and other materials often have problems such as loose bonding and separation from the material. As a result, the mechanical properties of BFRP cannot reach the expected effect of the theory. In the impregnation fusion method, the requirements for the mix ratio of basalt fiber and other materials under different substrates will also be more stringent. However, as far as the current technology is concerned, the design and planning of the mix ratio and its process still have a large room for development.

4.2.3 The difficulties in interface modification

At present, the interface modification method is mainly used to solve the problem that the fiber and other materials in BFRP are not tightly bonded. Although it can increase the specific surface area and increase the bond strength between the interfaces, each modification method has certain limitations and cannot achieve large-scale production. At present, there is a lack of systematic analysis of the mixture ratio scheme of BF interface modification under different substrates, the final effect of modification and the actual situation of application.

4.2.4 The application difficulty in civil engineering industry

Although BFRP has been widely used in the concrete structure and reinforcement field in the civil engineering industry, there are still some problems [13]. First, because most of today’s studies focus on the strength, corrosion resistance and porosity of BFRP specimens, there is a lack of application data and statistics on the environmental performance of BFRP materials in actual civil engineering applications. Secondly, in China, although there have been many regulations on BFRP, such as GB/T 23265-2009 “Chopped Basalt Fiber for cement Concrete and mortar”, it is difficult to specify perfect specifications for BFRP production and quality inspection [17]. Last but not the least, in terms of performance improvement, there is no research to show which method is the most cost-effective, so it is still difficult to put BFRP into application in the civil industry. Therefore, a series of systematic studies and formulating a set of market specifications that meet the characteristics of BFRP is necessary.

5. Conclusion

This paper mainly studies the preparation process, mechanical properties and influencing factors of BF and BFRP, as well as the advantages and development difficulties compared with other fiber composites. The main conclusions are as follows:

(1) In the preparation of BF and BFRP, due to the different properties of basalt ores in different regions, it is impossible to make all products reach the desired quality at the same time in the preparation. In the future research, it is necessary to carry out systematic research on basalt ores in various regions and form a perfect database, and then improve the preparation methods of BF and BFRP accordingly.

(2) In terms of modification, although each modification method can improve the mechanical properties of BF in a certain aspect, there is still a lack of systematic research on the situation put into practical application. The deterioration of interface aging caused by light and temperature rise, such as fatigue life, still needs more research to find solutions.

(3) Although BF and BFRP have many advantages over other fiber composites, there are still many problems to be solved. For example, the performance data of basalt ore is incomplete, the use of BFRP specifications are still defective, and which modification method should be used, and so on. All these problems need more research and improvement to make BF and BFRP have better development and better application in the civil engineering industry in the future.

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