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Research Progress on Basalt Fiber-Reinforced Recycled Concrete

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ABSTRACT: Basalt Fiber-Reinforced Recycled Concrete (BFRRC), as an important development direction of green building materials, has received extensive attention in recent years. This paper systematically reviews the research progress on the mechanical properties, durability, microscopic mechanism, and structural applications of basalt fiber-reinforced recycled concrete. In terms of mechanical properties, basalt fiber can improve the compressive, tensile, and shear performance of recycled concrete, but the improvement effect is affected by factors such as fiber content and matrix strength. Regarding durability, basalt fiber can effectively enhance the frost resistance, carbonation resistance, and salt erosion resistance of recycled concrete, and there exists an optimal dosage range within 0.1%~1.0% fiber content. Microscopic studies show that fibers form a network structure in the matrix, inhibit crack propagation, and improve the performance of the interfacial transition zone. At the level of structural application, basalt fiber-reinforced recycled concrete beams and columns exhibit favorable mechanical performance, and the combined application of fiber-reinforced bars and fiber-reinforced recycled concrete has become a research hotspot. However, existing studies still suffer from problems such as insufficient long-term performance data, unclear deterioration mechanism under multi-factor coupling, and lack of standardized design methods. Future research should focus on the multi-scale collaborative reinforcement mechanism, the development of intelligent life prediction models, and the establishment of technical standards for engineering applications.

KEYWORDS: basalt fiber, recycled concrete, mechanical properties, durability, microstructure, structural application.

I. INTRODUCTION

With the continuous expansion of infrastructure construction in China, natural aggregate resources are becoming increasingly scarce. Meanwhile, the output of construction waste is rising year by year, resulting in growing pressure on resources and the environment. Recycled concrete technology replaces natural aggregate with crushed waste concrete, which can not only solve the problem of construction waste disposal but also alleviate the shortage of natural aggregate, conforming to the concept of sustainable development ^[1]. However, due to the presence of attached mortar, recycled concrete has high porosity and a complex interfacial transition zone, leading to inferior mechanical properties and durability compared with natural concrete, which restricts its popularization and application in structural engineering ^[1,2].

Fiber reinforcement technology provides an effective way to improve the properties of recycled concrete. As a green inorganic fiber, basalt fiber has high tensile strength, good chemical stability, and excellent compatibility with cement-based materials, showing promising application prospects in the modification of recycled concrete ^[1,3]. In recent years, scholars at home and abroad have carried out extensive research on basalt fiber-reinforced recycled concrete, covering material properties, durability, microscopic mechanism, component performance, and other aspects. Nevertheless, the relevant research results are relatively scattered and lack systematic review.

This paper aims to present a comprehensive review of the research progress of basalt fiber-reinforced recycled concrete. The existing research results are analyzed from the dimensions of mechanical properties, durability, microscopic mechanism, and structural application. The main conclusions are summarized, the deficiencies in current research are

pointed out, and future research directions are prospected, so as to provide a reference for the further research and engineering application in this field.

II. MECHANICAL PROPERTIES OF BASALT FIBER-REINFORCED RECYCLED CONCRETE

2.1 Basic Mechanical Properties

Studies on the influence of basalt fiber on the basic mechanical properties of recycled concrete have been relatively systematic, mainly including compressive strength, splitting tensile strength, flexural strength, and other aspects. The recycled concrete aggregate and basalt fiber are shown in Figure 1.



Figure 1 Schematic diagram of recycled aggregate and fiber

Regarding compressive strength, research conclusions show some differences. Some studies indicate that basalt fiber has a limited improvement effect on the compressive strength of recycled concrete, and may even cause a slight reduction. Experimental research on the mechanical properties of hybrid fiber-reinforced recycled concrete after high temperatures found that, compared with plain recycled concrete, the compressive strength of recycled concrete increased when basalt fiber and cellulose fiber were added together, and the optimal compressive strength was achieved when the content of both fibers was 0.15% [4]. A study on the axial mechanical behavior of short circular steel tubes filled with basalt fiber-reinforced recycled concrete showed that with the increase of basalt fiber content, the bearing capacity of the core concrete increased slightly, while the energy dissipation capacity and ductility coefficient increased gradually [5]. Such differences may be related to fiber content, matrix strength, test conditions, and other factors.

In terms of tensile performance, the strengthening effect of basalt fiber is more significant. Studies have shown that the addition of basalt fiber can improve the brittle failure characteristics of recycled concrete and lead to a ductile failure mode [6]. Mechanical tests after high temperatures revealed that the splitting tensile strength of recycled concrete was significantly improved when the basalt fiber content ranged from 0.10% to 0.15% [5]. A study on the pore properties of basalt fiber-reinforced recycled concrete in salt erosion environment found that the optimal compressive and splitting tensile strengths were obtained at a fiber content of 1.0% [7].

2.2 Dynamic Mechanical Properties

The dynamic mechanical properties of recycled concrete are crucial for its application in seismic, impact-resistant and other scenarios. Reference [8] reviewed the research status of dynamic mechanical properties of recycled concrete, pointing out that the dynamic mechanical properties of recycled concrete are inferior to those of natural concrete, and the addition of fiber reinforcement and modification can effectively improve its dynamic response characteristics. Studies have shown that fiber-reinforced recycled concrete exhibits obvious rate sensitivity under high strain rates, and the dynamic strength increase factor rises with the increase of strain rate. At present, research in this field is still in the preliminary stage, and studies on the dynamic constitutive relationship and energy dissipation mechanism of basalt fiber-reinforced recycled concrete are insufficient [9].

2.3 Mechanical Properties After High Temperature

The degradation law of mechanical properties of recycled concrete under high temperature is an important basis for fire safety assessment. A study on the high-temperature performance of modified recycled concrete tested specimens at 25, 200, 400 and 600 °C. It was found that with the increase of temperature, the mass loss rate of recycled concrete increased, the compressive strength decreased, and the performance degradation of the mortar matrix, interfacial transition zone, and the bonding behavior between fiber and mortar became more severe (As shown in Figure 2). The study also found that the mass content of basalt fiber had no obvious effect on compressive performance, while the incorporation of nano-silica was more effective in improving high-temperature performance [2]. Experimental research on the mechanical properties of hybrid fiber-reinforced recycled concrete after high temperatures established the relationship between the relative compressive strength, relative splitting tensile strength and temperature of fiber-reinforced recycled concrete after different high temperatures, providing a reference for post-high-temperature performance evaluation [5].

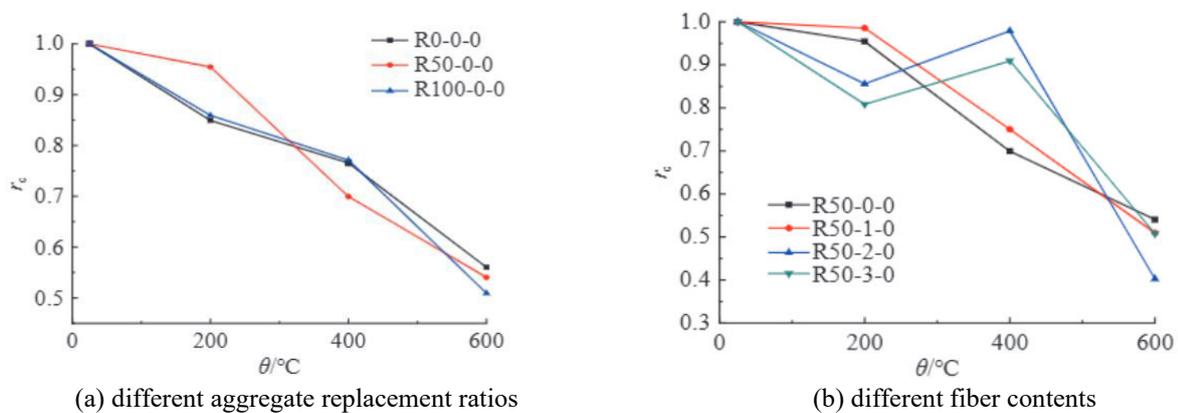


Figure 2 Curve of residual compressive strength versus temperature

III. DURABILITY PERFORMANCE OF BASALT FIBER-REINFORCED RECYCLED CONCRETE

3.1 Frost Resistance

Frost resistance is a key index for the application of recycled concrete in alpine and cold regions. Studies on the frost resistance of basalt fiber-iron tailings recycled concrete show that adding basalt fiber into recycled concrete can improve its frost resistance, and fiber content has a significant influence. In the test, specimens with a fiber content of 0.1% and a fiber length of 18 mm exhibited the lowest strength loss rate after freeze-thaw cycles [1]. Iron tailings sand can alleviate freeze-thaw damage of recycled concrete; when the content is less than 30%, the freeze-thaw damage decreases with the increase of iron tailings sand content [3].

Studies on the frost resistance of basalt-polyvinyl alcohol (PVA) hybrid fiber-reinforced recycled concrete are relatively systematic. It is found that adding external fibers can improve the frost resistance of recycled concrete, and the effect of hybrid fibers is better than that of single fiber. The two types of fibers form a network distribution inside the specimen, bear loads synergistically, and constrain the matrix mutually, thus greatly restricting the propagation and number of cracks. The response surface method was used to optimize the fiber content. The results show that the frost resistance of recycled concrete is optimal when the volume contents of PVA fiber and basalt fiber are 0.170% and 0.246%, respectively [10, 11].

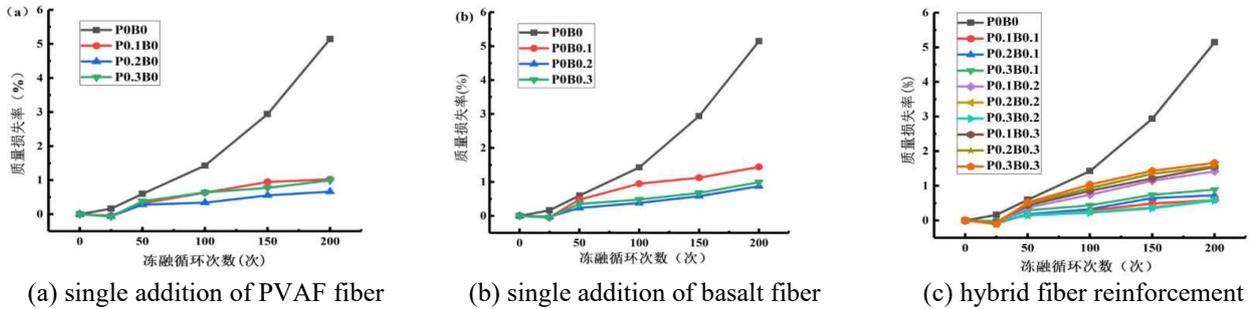


Figure 3 Mass loss rate of specimens with different fiber additions

A study on the bond performance between fiber-reinforced recycled concrete and BFRP bars under freeze-thaw cycles shows that secondary hydration of concrete occurs with the increase of freeze-thaw cycles, leading to an improvement in the ultimate bond strength [10]. This finding is valuable for the composite application of fiber-reinforced recycled concrete and fiber bars in cold regions.

3.2 Carbonation Resistance

The carbonation resistance of recycled concrete directly affects the durability of reinforced concrete structures. Research on the effect of basalt fiber on the carbonation resistance of recycled concrete shows that the carbonation depth of recycled concrete increases with the increase of carbonation time. With the increase of recycled coarse aggregate replacement ratio, the carbonation depth first decreases and then increases. The best carbonation resistance is achieved at a 50% mass replacement ratio of recycled coarse aggregate. Adding basalt fiber can effectively improve the carbonation resistance of recycled concrete. With the increase of fiber content, the carbonation resistance first increases and then decreases, with the optimal content being 2 kg/m³. A carbonation depth model of basalt fiber-reinforced recycled concrete was also established, providing a basis for carbonation life prediction [13].

3.3 Durability in Salt Erosion Environment

Salt erosion poses a major threat to the durability of concrete structures in coastal and saline soil areas. A study on durability evaluation and life prediction of basalt fiber-reinforced recycled concrete under coupled salt-dry-wet cycling established a comprehensive durability index D based on the entropy weight method to evaluate the durability of recycled concrete. The results show that the D-value of specimens gradually decreases with an increasing rate as the number of salt solution dry-wet cycles increases. The addition of basalt fiber can effectively increase the D-value and improve the durability of recycled concrete, with the best improvement at a fiber content of 1.0%. The established GM(1,1) mean model can accurately predict the time-varying law of the D-value of recycled concrete under coupled salt-dry-wet erosion [4].

A study on pore properties and life prediction of basalt fiber-reinforced recycled concrete under salt erosion analyzed the internal changes of concrete using scanning electron microscopy (SEM) and established a linear regression model among concrete porosity, number of dry-wet cycles, penetration height, compressive strength, and splitting tensile strength. It is found that the porosity gradually increases with the erosion age, and an appropriate amount of basalt fiber can significantly reduce the porosity of concrete, with the most significant effect at 1.0% fiber content. A fully connected neural network model was adopted to predict the erosion resistance life of basalt fiber-reinforced recycled concrete in salt erosion environments, providing a new method for service life prediction [7].

IV. MICROSTRUCTURE AND REINFORCEMENT MECHANISM

4.1 Fiber Distribution and Interface Structure

The improvement of the microstructure of recycled concrete by basalt fiber is the intrinsic reason for the enhancement of its macroscopic properties. Scanning electron microscope (SEM) observations show that basalt fibers are distributed in a network form inside the specimen and constrain the matrix mutually, thus effectively restricting the propagation and quantity of cracks [8]. A study on the frost resistance of basalt fiber-iron tailings recycled concrete found via SEM

analysis that the incorporation of fibers improved the microstructure of recycled concrete and alleviated freeze-thaw damage (As shown in Figure 4) [3].

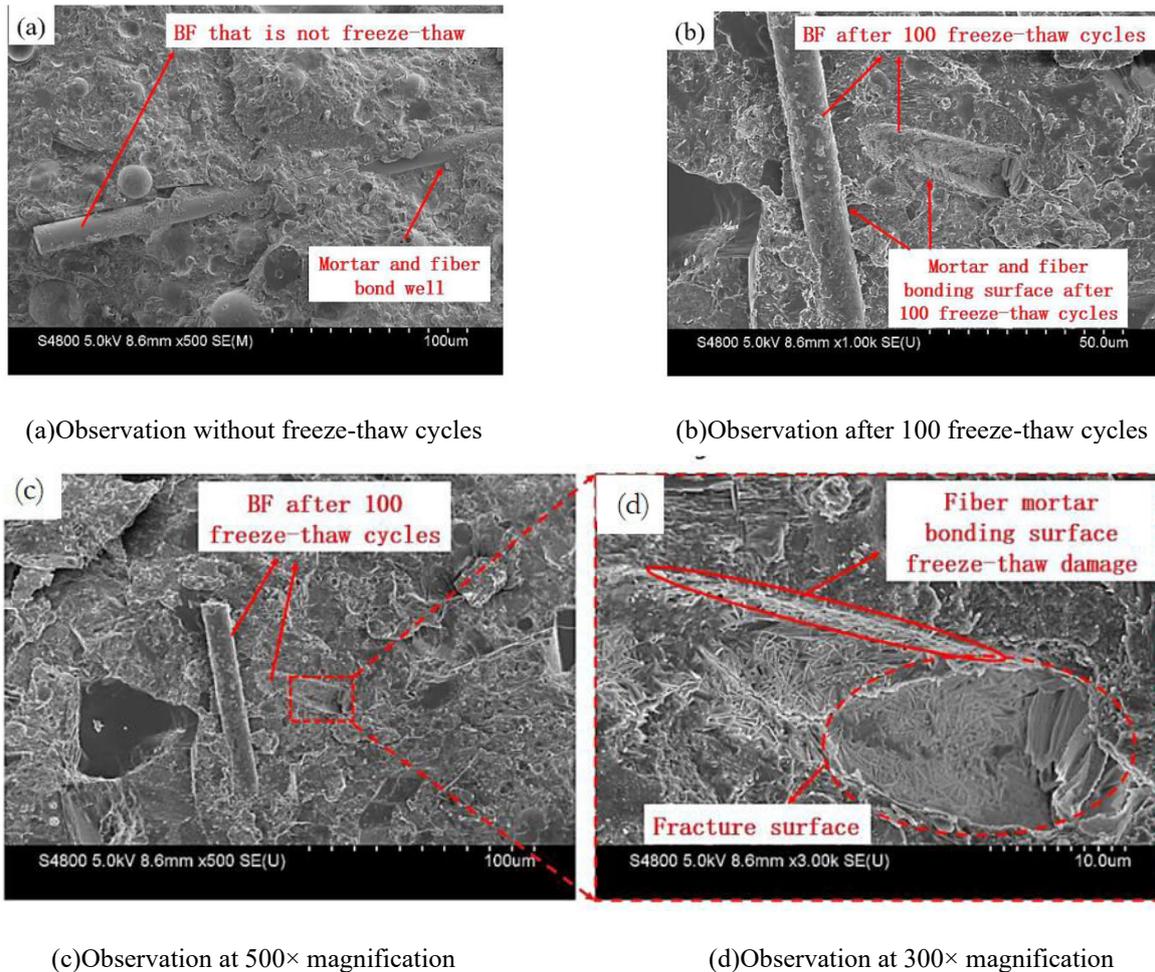


Figure 3 Schematic diagram of the microstructure of specimens after freeze-thaw cycles

A study on the pore structure and mechanical properties of 3D-printed fiber-reinforced recycled fine aggregate concrete used computed tomography (CT) for visual analysis of 3D-printed concrete samples. It was found that the pores in 3D-printed recycled concrete samples were distributed in an ellipsoidal orientation, and the incorporation of fibers influenced the directional trend of pores. The addition of polyethylene fiber and basalt fiber resulted in a decrease in the average pore compactness. The proportion of pores perpendicular to the Z-axis increased in 3D-printed recycled concrete samples with polyethylene fiber, while it decreased in samples with basalt fiber [14].

4.2 Interfacial Transition Zone and Hydration Products

A study on the high-temperature performance of modified recycled concrete, combined with SEM and X-ray diffraction (XRD) analysis, found that with the increase of temperature, the performance degradation of the mortar matrix, interfacial transition zone, and the bonding behavior between fiber and mortar became more severe, accompanied by the reduction of CH crystals and C-S-H gel concentration. With the increase of recycled coarse aggregate replacement ratio and nano-silica content, the mass loss rate increased, the compressive strength decreased, and the mortar matrix became loose [2].

4.3 Hybrid Fiber Reinforcement Effect

Studies on basalt-polyvinyl alcohol (PVA) hybrid fiber reinforcement show that the two types of fibers are distributed in a network inside the specimen, bear load synergistically, and constrain the matrix mutually, which greatly restricts the propagation and quantity of cracks [8,9]. The reinforcement effect of hybrid fibers is better than that of single fiber, reflecting the synergistic effect of fiber hybridization. Experimental research on the mechanical properties of hybrid fiber-reinforced recycled concrete after high temperature also confirmed that hybrid fibers can reduce surface spalling and mass loss of recycled concrete, and transform the failure mode from brittle failure to ductile failure [5].

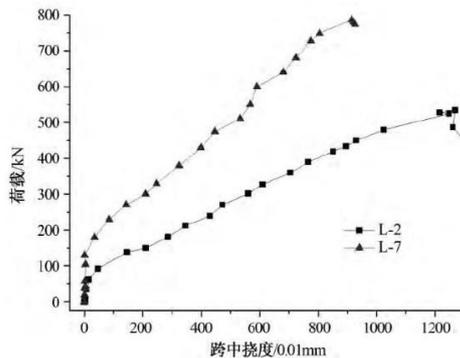
V. RESEARCH ON MECHANICAL PERFORMANCE OF BASALT FIBER-REINFORCED RECYCLED CONCRETE MEMBERS

5.1 Mechanical Behavior of Beam Members

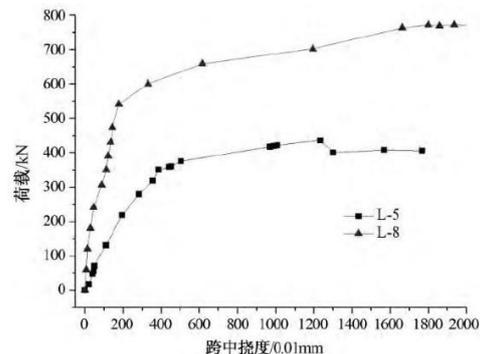
An experimental study on the flexural behavior of basalt fiber-reinforced polymer (BFRP) bars and steel fiber-reinforced recycled concrete beams investigated the effects of steel fiber volume fraction and BFRP reinforcement ratio on flexural performance. The results showed that both steel fiber content and reinforcement ratio had a significant influence on the flexural capacity. Compared with BFRP-reinforced recycled concrete beams without steel fibers, the initial cracking load and ultimate load of the test beams with 1.0% steel fiber volume fraction were increased by 32.8% and 18.2%, respectively [15].

A study on the shear behavior of stirrup-free BFRP bar-reinforced recycled concrete beams analyzed the effects of recycled coarse aggregate replacement ratio, shear span ratio, and reinforcement ratio on shear capacity. It was found that the shear capacity of BFRP-reinforced recycled concrete beams was lower than that of BFRP-reinforced natural concrete beams. By comparing the test results with formulas recommended by technical standards of various countries, the Canadian standard CSA.S 806-12 showed better agreement and safety margin [16].

An experimental study on the deflection of BFRP-reinforced recycled concrete beams compared the deflection between BFRP-reinforced and steel-reinforced recycled concrete beams. Under the same load, the deflection of BFRP-reinforced recycled concrete beams was larger but with poorer ductility. The deflection of test beams decreased with the increase of section height and stirrup ratio [17].

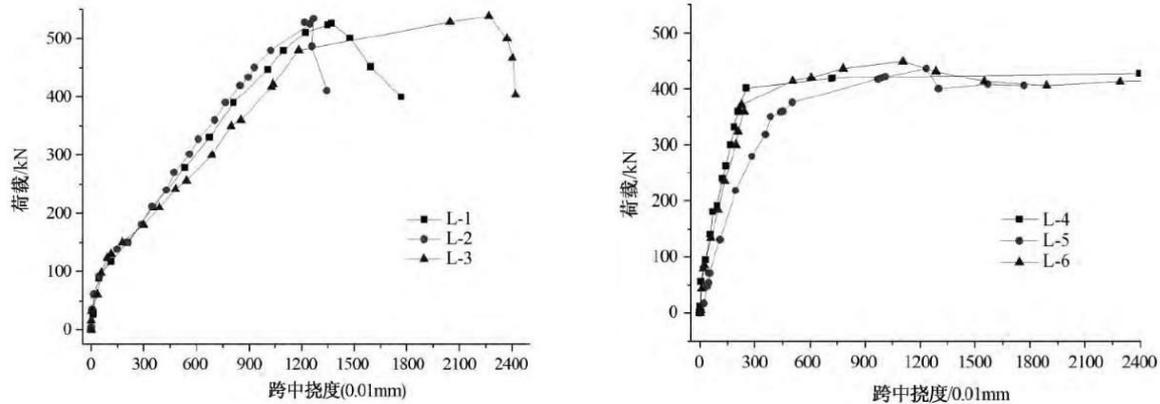


Mid-span deflection of L-2 and L-7



Mid-span deflection of L-5 and L-8

Effect of different section heights on mid-span deflection of beams
(Section heights of L-7 and L-8 are 400 mm, while those of L-2 and L-5 are 300 mm)



Mid-span deflection of L-1, L-2 and L-3

Mid-span deflection of L-4, L-5 and L-6

Effect of different stirrup spacings on mid-span deflection of beams
(Stirrup ratio: L-1, L-4 > L-2, L-5 > L-3, L-6)

Figure 4 Schematic diagram of mid-span deflection variation of beams under different section heights and stirrup ratios

An experimental study on the fatigue performance of basalt fiber-reinforced recycled concrete box girders designed a composite box girder with corrugated steel webs and basalt fiber-reinforced recycled concrete, and conducted four-point bending variable-amplitude fatigue tests. It was found that the fiber-reinforced recycled concrete box girder exhibited favorable variable-amplitude fatigue resistance. The recycled coarse aggregate replacement ratio was the main factor affecting the fatigue life under variable amplitude. CFRP strengthening could effectively restrain fatigue crack propagation and longitudinal slip, thus improving the fatigue life of the composite structure [18].

5.2 Mechanical Behavior of Column Members

An experimental study on the axial compressive behavior of short circular steel tube columns filled with basalt fiber-reinforced recycled concrete was carried out with recycled coarse aggregate replacement ratio and basalt fiber content as variables. All specimens failed by outward buckling, while the core concrete remained relatively intact under the confinement of the steel tube. With the increase of recycled coarse aggregate replacement ratio, the energy dissipation capacity and ductility coefficient increased gradually, while the bearing capacity decreased gradually. With the increase of basalt fiber content, the energy dissipation capacity and ductility coefficient increased gradually, but the improvement in bearing capacity was limited [6].

An experimental study on the eccentric compressive behavior of short square steel tube columns filled with basalt fiber-reinforced recycled concrete was performed under static eccentric loading, with parameters including recycled coarse aggregate replacement ratio, basalt fiber content, strength grade of recycled concrete, and eccentricity. The peak bearing capacity of specimens decreased with the increase of replacement ratio or eccentricity, and increased with the increase of core recycled concrete strength. The established finite element model could effectively simulate the whole process of eccentric mechanical behavior [19].

VI. RESEARCH ON MULTI-MATERIAL COMPOSITE AND FUNCTIONALIZATION

6.1 Hybrid Fiber System

The hybrid application of basalt fiber with other fibers has become a research hotspot. Studies on the basalt-polyvinyl alcohol (PVA) hybrid fiber system show that hybrid fibers perform better than single fiber. The two types of fibers are distributed in a network inside the specimen and bear load synergistically, which greatly restricts crack propagation.

A study on the mechanical properties of hybrid fiber-reinforced recycled concrete after high temperature explored the hybrid effect of cellulose fiber and basalt fiber. It was found that hybrid fibers can reduce surface spalling and mass loss of recycled concrete, thus improving the mechanical properties after high temperature [5].

6.2 Synergy with Mineral Admixtures

The synergistic application of basalt fiber and mineral admixtures has also attracted extensive attention. Research on basalt fiber-iron tailings recycled concrete indicates that iron tailings sand can alleviate freeze-thaw damage of recycled concrete, and the frost resistance can be further improved when combined with basalt fiber [1].

A study on the high-temperature performance of modified recycled concrete investigated the synergistic effect of basalt fiber and nano-silica, and found that nano-silica is more effective in improving high-temperature performance [8].

6.3 Functionalized Recycled Concrete

A performance study on high-performance recycled pervious fiber concrete was conducted by adding basalt fiber, cotton fiber, carbon fiber and polypropylene fiber into concrete respectively. The optimal fiber content was determined by testing the slump, density, permeability coefficient and compressive strength of pervious concrete.

It was found that cotton fiber can endow concrete with high compressive strength, and the optimal content of cotton fiber in pervious concrete is suggested to be 6% [20].

Research on 3D-printed fiber-reinforced recycled fine aggregate concrete explores the application of fiber-reinforced recycled concrete in 3D printing technology. The pore structure and anisotropic characteristics of mechanical properties of 3D-printed specimens are analyzed, which provides a foundation for digital construction of recycled concrete [21].

VII. RESEARCH DEFICIENCIES AND FUTURE PROSPECTS

7.1 Deficiencies in Existing Research

Based on the above analysis, current studies on basalt fiber-reinforced recycled concrete still have the following deficiencies:

- (1) Lack of long-term performance data. Most existing studies focus on short-term performance tests, and systematic research on the long-term performance of basalt fiber-reinforced recycled concrete (such as long-term shrinkage, creep, fatigue performance) is insufficient, which makes it difficult to support its popularization and application in important structures.
- (2) Insufficient research on multi-factor coupling effects. In practical engineering, concrete structures are often subjected to the coupling effects of load and environmental factors (freeze-thaw, carbonation, salt erosion, etc.). However, most existing studies only consider single or simple dual factors, and the performance degradation law and deterioration mechanism under multi-factor coupling are still unclear.
- (3) Inadequate correlation between microscopic mechanism and macroscopic performance. Although some studies have carried out microscopic observations by means of SEM and other techniques, most of them are qualitative descriptions, and there is a lack of quantitative correlation models between microstructure parameters and macroscopic properties.
- (4) Absence of standardized design methods. At present, there are no unified technical standards for material design, performance testing, member calculation, etc. of basalt fiber-reinforced recycled concrete, which creates obstacles to the transformation of research results into engineering applications.
- (5) Imperfect evaluation system for fiber reinforcement effect. Parameters such as fiber content, length and type vary greatly in different studies, and evaluation indicators are not unified, resulting in poor comparability of research results and difficulty in forming universal conclusions.

7.2 Future Research Directions

Based on the existing research progress and deficiencies, future research on basalt fiber-reinforced recycled concrete can focus on the following directions:

- (1) Research on multi-scale collaborative reinforcement mechanism. Systematically investigate the interaction mechanism between basalt fiber and each phase component of recycled concrete from molecular, microscopic to

macroscopic scales, and establish a multi-scale reinforcement theoretical model to provide theoretical guidance for material optimization design.

(2) Development of intelligent life prediction methods. Combined with artificial intelligence algorithms (neural network, grey model, etc.) and classical durability theory, develop life prediction models considering multi-factor coupling effects to improve prediction accuracy and application scope.

(3) Research and development of high-performance composite structural systems. Combine basalt fiber-reinforced recycled concrete with FRP bars, steel tubes and other components to develop new composite structural systems, give full play to the performance advantages of each material, and improve the overall structural performance.

(4) Optimization design of hybrid fibers. Systematically study the hybrid effect of basalt fiber with different fibers (polyvinyl alcohol fiber, cellulose fiber [11], steel fiber [14], etc.), and establish a performance optimization design method for hybrid fiber-reinforced recycled concrete.

(5) Application of digital construction technology. Combined with digital construction technologies such as 3D printing, explore the application of fiber-reinforced recycled concrete in special-shaped members and complex structures to expand its application fields.

(6) Establishment of technical standard system. On the basis of systematic research, formulate technical standards for materials, design, construction and acceptance of basalt fiber-reinforced recycled concrete to provide technical support for its engineering application.

VIII. CONCLUSIONS

(1) Basalt fiber can improve the mechanical properties of recycled concrete, and its strengthening effect on tensile performance is better than that on compressive performance. There exists an optimal fiber content range within 0.1%–1.0%, and the reinforcement effect of hybrid fibers is superior to that of single fiber.

(2) Basalt fiber can effectively enhance the frost resistance, carbonation resistance and salt erosion resistance of recycled concrete. Fiber content and recycled aggregate replacement ratio are key parameters affecting durability. The comprehensive durability evaluation method based on the entropy weight method and intelligent life prediction models provide new tools for durability research.

(3) Microscopic studies show that basalt fibers form a network structure in the matrix, restrain crack propagation and improve the properties of the interfacial transition zone. Factors such as temperature and corrosive environment have a significant influence on the fiber–matrix interfacial bond performance.

(4) Basalt fiber-reinforced recycled concrete beams and columns exhibit favorable mechanical performance. The combined application of fiber-reinforced polymer bars and basalt fiber-reinforced recycled concrete presents a synergistic effect. Most existing studies on members focus on short-term static performance, while research on fatigue performance remains insufficient.

(5) Future research should focus on the multi-scale collaborative reinforcement mechanism, deterioration mechanism under multi-factor coupling, development of intelligent life prediction methods, and establishment of technical standards for engineering applications, so as to promote the transformation of basalt fiber-reinforced recycled concrete from material research to engineering application.

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