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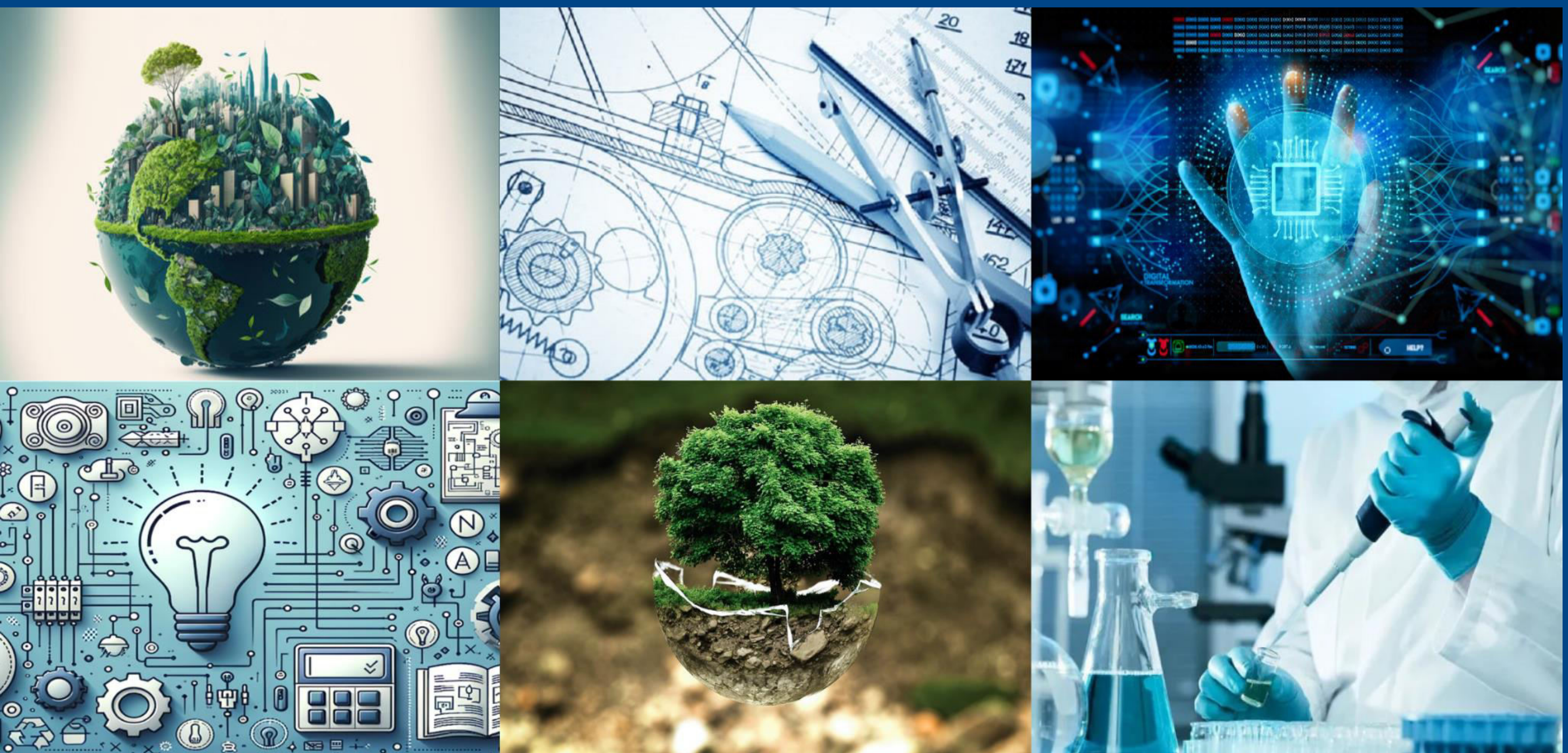

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Study on the Compressive Constitutive Relationship and Damage Evolution Model of Basalt Fiber Recycled Concrete

Zhixin LI, Ze LI, Peng ZHANG, Jun LIU, Xinzhong Wang

School of Civil Engineering, Hunan City University, Yiyang, Hunan, China

ABSTRACT: Recycled concrete has attracted considerable attention because of its value in resource recycling and reuse. However, defects in the interfacial transition zone of recycled aggregates, high porosity, and the ease of crack propagation result in inferior strength, ductility, and durability compared with ordinary concrete to varying degrees. Basalt fiber, characterized by high strength, good corrosion resistance, and strong crack-bridging capability after dispersion, is regarded as an effective means of improving the mechanical performance and service stability of recycled concrete. Based on 15 related studies, this paper systematically reviews the compressive mechanical behavior, damage evolution characteristics, and model construction methods of basalt fiber recycled concrete. The results indicate that basalt fiber can effectively inhibit crack propagation and improve the peak strain, toughness, and energy absorption capacity of recycled concrete. Its reinforcing effect generally exhibits a trend of "increasing first and then decreasing," indicating the existence of an optimal dosage range. During compressive failure, the material shows obvious stage-wise evolution characteristics, and under freeze–thaw cycles, salt erosion, sulfate attack, and fatigue loading, the damage variable continuously develops with increasing environmental deterioration or loading cycles. Current studies on constitutive behavior and damage mainly follow the path of "stress–strain relationship fitting—damage variable definition—life prediction," but deficiencies remain in the unified description of the whole compressive process, the characterization of environment-coupled damage, and the collaborative identification of parameters. On this basis, a compressive constitutive analysis approach and a damage evolution model framework suitable for basalt fiber recycled concrete are proposed, with the aim of providing theoretical references for constitutive expression, durability evaluation, and engineering application of this material.

KEYWORDS: basalt fiber; recycled concrete; compressive constitutive relationship; damage evolution; energy dissipation; life prediction

I. INTRODUCTION

Against the background of the "dual-carbon" goals and the resource utilization of construction solid waste, recycled concrete has become an important research direction in civil engineering materials because it enables the reutilization of waste concrete. However, owing to the adhered old mortar on the surface of recycled aggregates, the large number of internal microcracks, and the high water absorption rate, recycled concrete exhibits inherent shortcomings in strength, deformation performance, and durability. In particular, during compressive failure, it is more prone to intensified brittleness, rapid crack penetration, and accelerated post-peak degradation of load-bearing capacity [1]. Therefore, how to improve the mechanical performance of recycled concrete through material modification and establish corresponding constitutive relationships and damage models has become a key issue in current research.

Basalt fiber is a new type of inorganic fiber material with high tensile strength, good durability, and strong interfacial bonding potential. When incorporated into recycled concrete, it can improve the internal stress state of the matrix through crack bridging, confinement, and crack dispersion mechanisms [2]. Existing studies have shown that basalt fiber can not only enhance the compressive and tensile properties of recycled concrete, but also improve peak strain, toughness, and fatigue resistance [3]. From the perspective of failure mechanism, basalt fiber plays a significant role in

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delaying crack initiation and propagation, which provides a basis for interpreting the compressive behavior of the material from the viewpoint of damage evolution [4].

At present, research on basalt fiber recycled concrete has gradually expanded from basic strength testing to the analysis of energy dissipation, fatigue life, freeze–thaw damage, and mechanical degradation under environmental erosion [5]. For example, some researchers have revealed, from an energy perspective, the influence of fibers on the energy storage limit and elastic energy release law during the compression failure process of concrete [4]. Under freeze–thaw cycling, fiber incorporation can slow down the decay of relative dynamic elastic modulus and strength, and corresponding damage deterioration models have been established accordingly [6]. In fatigue studies, methods such as Weibull distribution and response surface methodology have been used to fit and predict fatigue life [7]. These achievements provide a basis for constructing compressive constitutive relationships and damage models, but three major deficiencies remain. First, the constitutive description of the entire compressive process is mostly based on local experimental phenomena and lacks a unified expression. Second, the definition of damage variables is still inconsistent, and the connection between mechanical damage and durability damage is insufficient. Third, the coupled effects of environmental actions and loading have not yet been fully incorporated into the constitutive analysis framework.

Based on this, the present paper systematically reviews the compressive constitutive relationship and damage evolution model of basalt fiber recycled concrete on the basis of existing literature. It focuses on analyzing its compressive mechanical behavior, stage-wise damage characteristics, model expression methods, and future optimization directions, so as to provide a useful theoretical foundation for subsequent experimental studies and model development.

II. COMPRESSIVE MECHANICAL BEHAVIOR CHARACTERISTICS OF BASALT FIBER RECYCLED CONCRETE

2.1 Improvement Pattern of Compressive Strength by Basalt Fiber

Compressive strength is the core index for characterizing the basic load-bearing capacity of recycled concrete. Studies have shown that an increase in the replacement ratio of recycled coarse aggregate generally reduces the axial compressive strength of concrete, whereas the incorporation of basalt fiber can, within a certain range, compensate for this adverse effect [1]. For recycled concrete with different strength grades and replacement ratios, the compressive strength generally increases with fiber content, but such an increase is not unlimited and is controlled by an optimal dosage [3]. This indicates that the reinforcing effect of basalt fiber on recycled concrete exhibits a threshold characteristic: an appropriate amount of fiber can improve the interfacial transition zone and alter crack propagation paths, whereas excessive fiber may weaken the strengthening effect because of poor dispersion, agglomeration, and reduced workability.

Judging from the available abstracts, conclusions regarding the optimal dosage are not entirely consistent across different studies, which is closely related to the strength grade of the specimens, the replacement ratio of recycled aggregate, the fiber length, and the incorporation method. For example, in axial compression studies, 0.1% basalt fiber produced the most obvious improvement in compressive strength [1]; whereas in specimens with different strength grades, a fiber dosage of 1.5 kg/m³ enabled part of the recycled concrete to reach a strength level close to that of ordinary concrete [3]. This suggests that the compressive constitutive parameters of basalt fiber recycled concrete cannot be simply described by a single “optimal dosage,” but should instead be identified comprehensively in combination with strength grade, recycled aggregate replacement ratio, and fiber parameters.

2.2 Characteristics of Compressive Deformation and Peak Strain

Compared with ordinary recycled concrete, the incorporation of basalt fiber brings more significant improvements in peak strain and deformation capacity. In studies on the mechanical properties after sulfate attack, basalt fiber was found to significantly enhance the peak strain and overall deformation capacity of recycled concrete, while its effect on the elastic modulus was not significant [8]. This phenomenon indicates that the main contribution of basalt fiber does not lie in markedly increasing the initial stiffness, but rather in improving deformation capacity and post-peak load-bearing stability during crack development.

Studies on size effect further show that both the peak stress and peak strain of basalt fiber recycled concrete are influenced by the specimen geometry. As the height-to-thickness ratio increases, both peak stress and peak strain decrease significantly [9]. This means that when establishing a compressive constitutive model, it is not sufficient to

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extrapolate solely from data obtained from specimens of a single size; instead, the effects of hoop action, crack propagation width, and specimen boundary conditions should be fully taken into account. In other words, the constitutive relationship reflects not only the intrinsic properties of the material, but also the specimen scale and confinement state.

2.3 Toughness and Energy Absorption Capacity

In constitutive analysis, it is insufficient to describe material properties only by peak strength and elastic modulus; the toughness and energy dissipation capacity in the post-peak stage are equally important. Existing studies have pointed out that, after the incorporation of basalt fiber, the compressive toughness of concrete under uniaxial compression generally increases with fiber volume fraction. The fiber significantly reduces the elastic energy release rate and increases the energy storage limit [4]. This indicates that basalt fiber can maintain a more gradual degradation process in the post-peak stage by bridging cracks, extending crack propagation paths, and increasing frictional energy dissipation.

Under freeze–thaw conditions, this strengthening effect on energy absorption still exists. Relevant studies have shown that the incorporation of basalt fiber can improve the energy absorption performance of recycled concrete, while the energy dissipation capacity of specimens gradually decreases with increasing numbers of freeze–thaw cycles, and the degree of mechanical damage continuously worsens [5]. Therefore, the energy perspective provides a sound explanation for the damage accumulation and toughness evolution of basalt fiber recycled concrete during compression, and also offers a strong physical basis for the construction of damage constitutive models.

III. DAMAGE EVOLUTION MECHANISM AND STAGE CHARACTERISTICS

3.1 Stage-Wise Evolution of Compressive Failure

The energy evolution of basalt fiber concrete under uniaxial compression can be divided into the compaction stage, energy storage stage, local failure stage, and accelerated elastic energy release stage [4]. This stage-wise feature is also applicable to understanding the compressive failure of basalt fiber recycled concrete. In the compaction stage, the initial pores and microcracks inside the material are gradually compacted, and the stress–strain curve shows a nonlinear upward trend. In the energy storage stage, the material is still dominated by elastic deformation as a whole, and crack development remains limited. In the local failure stage, cracks begin to propagate in the interfacial transition zone, and the crack-bridging effect of fibers gradually becomes evident. In the post-peak stage, rapid release of elastic energy and penetration of macrocracks occur. If the fiber dosage is appropriate, the descending branch after the peak becomes relatively gentle.

Under cyclic loading and fatigue conditions, the stage-wise character of damage evolution becomes even more evident. Studies have found that both the fatigue strain and fatigue modulus of basalt fiber recycled concrete develop in three stages, and an increase in fiber volume fraction can slow down the growth of fatigue strain and the degradation of fatigue modulus [7]. Similarly, in the analysis of compressive fatigue life, the fatigue life of the material is improved under different fiber dosages and aspect ratios, but an increase in stress level significantly accelerates the accumulation of fatigue damage [10]. This indicates that, under either static or cyclic loading, the damage evolution of basalt fiber recycled concrete follows a common pattern, namely, from initial stability to accelerated development in the middle and later stages.

3.2 Damage Accumulation under Environmental Actions

Compared with simple compression, environmental actions make the damage mechanism of basalt fiber recycled concrete more complex. Freeze–thaw cycles reduce longitudinal wave velocity, relative dynamic elastic modulus, and strength indices, and damage develops more rapidly in the later freeze–thaw stages [5]. Damage deterioration models established on the basis of relative dynamic elastic modulus and strength indicate that basalt fiber can delay the development of freeze–thaw damage in recycled concrete, but cannot prevent the continuous accumulation of damage with increasing cycle numbers [6]. This conclusion shows that the role of fiber in damage evolution is essentially to "delay" rather than to "eliminate" damage.

Salt erosion and chloride penetration mainly affect damage evolution by altering the pore structure and interfacial state of the material. Under salt erosion, porosity increases with erosion age, while an appropriate amount of basalt fiber can significantly reduce porosity and improve compressive strength and splitting tensile strength [11]. Studies on chloride penetration show that basalt fiber can reduce porosity by optimizing hydration products and pore size distribution, thereby improving resistance to penetration [12]. These microscopic changes imply that, in the construction of constitutive relationships, pore structure evolution should be regarded as an important prerequisite for the formation of damage variables.

Under sulfate attack, the recycled aggregate replacement ratio and fiber dosage jointly influence the compressive strength, elastic modulus, and peak strain [8]. By introducing a superposition effect coefficient to analyze the full load–displacement curve and failure mechanism, researchers have shown that environmental erosion and loading do not simply superimpose, but may instead exhibit coupling amplification or mutual inhibition effects. This provides important inspiration for the subsequent establishment of environment–load coupled damage models.

3.3 Relationship between Microstructure and Damage Evolution

The essence of damage evolution lies in the initiation, propagation, and coalescence of internal pores, microcracks, and interfacial defects. Carbonation studies have shown that, with increasing carbonation age, the pore structure of specimens changes significantly: porosity decreases in the early stage, whereas strength deteriorates in the later stage, and the strength reduction of fiber concrete is lower than that of plain concrete [13]. Although the object of this study is not recycled concrete, the revealed relationship between "pore structure evolution and transformation of mechanical properties" still provides useful insights for basalt fiber recycled concrete.

For recycled concrete, the interfacial transition zone of recycled aggregate itself is relatively weak, and microcracks are more likely to propagate under the combined action of compression and environmental erosion. On the one hand, the incorporation of basalt fiber delays crack opening through physical bridging; on the other hand, it improves matrix compactness by enhancing the aggregation of hydration products and optimizing pore size distribution [12]. Therefore, damage variables should not be defined solely from the perspective of mechanical indices, but should also incorporate parameters such as porosity, dynamic elastic modulus, and wave velocity, so as to build a multi-index coupled damage description system.

IV. CONCEPTUAL FRAMEWORK FOR CONSTRUCTING THE COMPRESSIVE CONSTITUTIVE RELATIONSHIP

4.1 Core Characterization Parameters of the Constitutive Relationship

From the existing studies, the establishment of the compressive constitutive relationship of basalt fiber recycled concrete should include at least four categories of core parameters: peak stress, peak strain, elastic modulus, and post-peak softening characteristics. Axial compression tests have shown that an increase in the replacement ratio of recycled coarse aggregate leads to a decrease in axial compressive strength, whereas a reasonable fiber dosage can partially compensate for this loss [1]. Studies on basic mechanical properties have also confirmed that basalt fiber exerts strengthening and toughening effects on both compressive strength and splitting tensile strength [2]. This indicates that the peak stress parameter should simultaneously reflect the combined effects of the deterioration caused by recycled aggregate and the enhancement induced by fiber incorporation.

Compared with peak stress, peak strain is more capable of reflecting the ductility advantage of basalt fiber recycled concrete. Studies have shown that the incorporation of basalt fiber significantly improves the peak strain and deformation capacity [8]. In axial tensile tests, both the initial cracking strain and peak strain exhibit a trend of first increasing and then decreasing, with the best performance occurring at a dosage close to 0.3% [14]. Although axial tension differs from compression, both results consistently suggest that the key role of basalt fiber lies in enhancing deformation coordination capacity after cracking. Therefore, in the compressive constitutive model, greater weight should be assigned to the peak strain parameter, so as to avoid representing the fiber reinforcing effect solely by strength variation.

4.2 Segmented Expression of the Compressive Constitutive Curve

Based on the existing studies, the stress–strain relationship of basalt fiber recycled concrete under compression may be divided into two basic intervals: the ascending branch and the descending branch. The ascending branch corresponds to the stages of compaction, elastic energy storage, and local microcrack development, and its curve shape is usually governed by the initial pore condition, elastic modulus, and peak stress. The descending branch corresponds to the rapid crack propagation and post-peak instability stages, and is more strongly influenced by the crack-bridging ability of fibers, the interfacial bonding performance, and the rate of damage accumulation [4].

Although a unified functional form has not yet been provided in the available abstracts, it can be seen from size-effect tests that the stress–strain curve has already been used as an important basis for analyzing peak stress, peak strain, and elastic modulus [9]. Studies on sulfate attack have further discussed the full load–displacement curve and failure mechanism [8]. This suggests that it is feasible to use segmented functions to describe the whole compressive process. For the ascending branch, a normalized stress–strain relationship may be adopted for fitting. For the descending branch, emphasis should be placed on reflecting the influence of fibers on the post-peak softening slope, so that the model can characterize the material features of "reduced brittle failure and delayed post-peak decline."

4.3 Constitutive Framework with Embedded Damage Variables

To achieve a unified expression of the constitutive relationship and damage evolution, it is necessary to introduce damage variables. In existing studies, freeze–thaw damage deterioration models are mostly established on the basis of relative dynamic elastic modulus and strength [6], indicating that damage variables may be defined in terms of stiffness degradation or load-carrying capacity deterioration. Studies on energy dissipation have shown that there is a clear correspondence among externally input energy, energy storage capacity, and energy dissipation capacity during the compressive process [5]. Therefore, damage evolution may also be defined from the perspective of energy dissipation.

Taken together, the damage constitutive relationship of basalt fiber recycled concrete may be developed along two paths. One is the "elastic modulus degradation type," in which material damage is represented by equivalent stiffness degradation. The other is the "energy dissipation type," in which the change in the proportion of irrecoverable energy within the external input energy is regarded as the process of damage accumulation. The former is convenient for engineering application and parameter acquisition, whereas the latter is more helpful for interpreting the physical mechanism between fiber bridging and crack propagation. If complete experimental data become available in future studies, the two approaches may also be combined to establish a composite damage constitutive model with stronger explanatory power.

V. ANALYSIS OF DAMAGE EVOLUTION MODELS AND PREDICTION METHODS

5.1 Deterioration Models Based on Strength and Dynamic Elastic Modulus

Among the existing studies, relatively mature damage models are mainly found in the field of freeze–thaw damage. Relevant literature has established linear and polynomial damage deterioration models based on indices such as mass loss rate, relative dynamic elastic modulus, compressive strength, and tensile strength, and has pointed out that these models can predict the development of freeze–thaw damage in fiber-reinforced recycled concrete with relatively high accuracy [6]. The advantage of this approach lies in the ease of parameter acquisition and the relatively high sensitivity of the selected indices, making it particularly suitable for durability evaluation and long-term service performance analysis.

However, from the perspective of compressive constitutive behavior, damage models constructed solely on the basis of macroscopic indices still have limitations. First, although dynamic elastic modulus and strength can reflect the overall degree of material degradation, they are unable to characterize in detail the microcrack propagation before the peak and the softening behavior after the peak. Second, a single damage variable can hardly characterize the coupled effects of environmental erosion and mechanical loading simultaneously. Therefore, future studies may consider incorporating variables such as wave velocity, porosity, peak strain, and energy-related parameters into multivariable damage models, so as to improve the adaptability of the model to the entire compressive process

5.2 Life Prediction Models Based on Probability Statistics and Fatigue Theory

In cyclic loading and fatigue analysis, the Weibull model is currently one of the most widely used methods. Studies have shown that the fatigue life of basalt fiber recycled concrete can be described by a three-parameter Weibull distribution to construct P - S–N curves, which are then used to analyze fatigue limit strength under different stress levels and survival probabilities [10]. Likewise, the flexural fatigue life of basalt fiber recycled concrete after freeze–thaw cycles also follows a two-parameter Weibull distribution, and the established double-logarithmic fatigue equation can effectively reflect the relationship between stress level and fatigue life [15]. These methods indicate that damage evolution can be characterized not only by continuous variables but also by life distribution and failure probability from a statistical perspective.

For research on compressive constitutive behavior, the significance of fatigue life models is not limited to life prediction itself, but also lies in the fact that they reveal the time-dependent and probabilistic characteristics of damage accumulation. Especially for materials such as recycled concrete, which exhibit considerable dispersion, probabilistic models are helpful for dealing with experimental fluctuations caused by the uneven distribution of internal defects. Therefore, when establishing a damage evolution model for basalt fiber recycled concrete, statistical distribution theory may be combined with continuous damage mechanics to form a dual-layer framework of “macroscopic constitutive relationship–probabilistic life prediction.”

5.3 Data-Driven Parameter Prediction Methods

With the development of research methodologies, some scholars have begun to identify key parameters through data-driven methods such as response surface methodology and neural networks. In fatigue studies, response surface methodology has been used to analyze the interaction effects of fiber volume fraction and stress level on fatigue life and to achieve multi-objective optimization [7]. In salt erosion studies, a fully connected neural network has been employed to establish a penetration height prediction model for evaluating the service life against erosion [11]. These methods indicate that, when there are many experimental parameters and complex coupling relationships among variables, traditional empirical formulas may be insufficient to accurately characterize the influencing mechanisms, whereas data-driven models provide new possibilities for parameter prediction and scheme optimization.

However, judging from the available abstract information, these data-driven methods are mainly used for predicting service life or performance indices and have not yet been truly integrated with the full compressive stress–strain process to form a constitutive expression. This means that future studies may further explore the use of peak stress, peak strain, elastic modulus, and damage variables as model outputs to construct intelligent prediction methods serving constitutive parameter identification, thereby realizing the integration of “experiment–model–prediction.”

VI. RESEARCH DEFICIENCIES AND FUTURE PROSPECTS

Based on the existing 15 studies, research on the compressive constitutive relationship and damage evolution of basalt fiber recycled concrete has made certain progress, but several obvious deficiencies still remain.

First, a unified constitutive model for the whole compressive process has not yet been established. Existing studies have largely remained at the level of analyzing individual indices such as compressive strength, peak strain, and elastic modulus. Although stress–strain curves and full-process load–displacement curves have been involved [9,8], there is still a lack of a unified compressive constitutive model capable of comprehensively reflecting the effects of recycled aggregate replacement ratio, fiber dosage, environmental damage, and size effect.

Second, the definition of damage variables remains rather fragmented. Some studies explain damage from the perspective of energy dissipation [5], some construct damage models based on dynamic elastic modulus and strength degradation [6], and others interpret material deterioration through porosity and microstructural changes [11,12]. Although each of these methods has its own advantages, a unified damage characterization framework integrating multiple scales and linking macro- and micro-levels has not yet been formed.

Third, research on environment–load coupling effects is still insufficient. Current studies have involved factors such as freeze–thaw cycles, salt erosion, chloride ions, carbonation, and sulfate attack [11,4,8,13], but most of them focus on single-factor analysis. There is still a lack of systematic investigation into how compressive constitutive parameters evolve and how damage variables change synergistically under multi-field coupled actions.

Fourth, the integration depth between data-driven methods and constitutive analysis remains inadequate. Methods such as response surface methodology and neural networks have already been applied in life prediction [11,3], but they have not yet been closely unified with stress–strain constitutive relationships and damage equations. In the future, if experimental data, microstructural features, and intelligent algorithms can be combined, the efficiency of model parameter identification and the accuracy of prediction may be significantly improved.

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Based on the above deficiencies, future research may be carried out in three directions. First, a standardized stress–strain database should be established through systematic uniaxial compression tests to clarify the constitutive evolution law under different recycled aggregate replacement ratios and fiber parameters. Second, macro–micro collaborative damage variables should be constructed from multiple aspects, including pore structure, interfacial transition zone, wave velocity variation, and energy dissipation. Third, continuous damage mechanics methods should be combined with statistical life models and data-driven models to form an integrated constitutive–damage framework applicable to basalt fiber recycled concrete under multiple environmental service conditions.

VII. CONCLUSIONS

Based on 15 related studies, this paper systematically analyzes the compressive constitutive relationship and damage evolution model of basalt fiber recycled concrete, and the following conclusions can be drawn:

First, basalt fiber can effectively improve the compressive performance of recycled concrete, mainly by enhancing compressive strength, peak strain, toughness, and energy absorption capacity. However, its reinforcing effect generally follows a pattern of “enhancement first and reduction thereafter,” indicating the existence of an optimal range associated with recycled aggregate replacement ratio, fiber dosage, and fiber length.

Second, the compressive failure of basalt fiber recycled concrete exhibits obvious stage characteristics, which may be summarized as the compaction stage, energy storage stage, local failure stage, and post-peak instability stage. Through crack bridging, stress dispersion, and delayed crack coalescence, basalt fiber improves the post-peak load-bearing retention capacity and deformation resistance of the material.

Third, environmental factors such as freeze–thaw cycles, salt erosion, chloride attack, and sulfate attack continuously accelerate damage accumulation, leading to increased porosity, degradation of elastic modulus, and strength deterioration. Although basalt fiber can delay the development of damage, it cannot fundamentally eliminate the environmental deterioration effect. Therefore, it is necessary to introduce environment-coupled damage variables into constitutive models.

Fourth, the current damage models for basalt fiber recycled concrete mainly include deterioration models based on strength and dynamic elastic modulus, fatigue life models based on Weibull distribution, and data-driven prediction models based on response surface methodology and neural networks. In the future, these methods should be further integrated with compressive stress–strain relationships to construct a unified constitutive–damage analytical framework. Overall, the proposed topic, “Study on the Compressive Constitutive Relationship and Damage Evolution Model of Basalt Fiber Recycled Concrete,” is generally well aligned with the existing literature base. If systematic uniaxial compression tests and full-process curve data are further supplemented, more innovative and convincing empirical research results can be obtained.

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