



International Journal of Innovative Research in Science Engineering and Technology (IJIRSET)

(A Monthly, Peer Reviewed, Refereed, Scholarly Indexed, Open Access Journal)



Impact Factor: 8.699

Volume 15, Issue 3, March 2026

Data-Driven Research Progress on Performance Prediction of Basalt Fiber Reinforced Concrete: From Empirical Models to Machine Learning

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ABSTRACT: Basalt fiber reinforced concrete (BFRC) combines the attributes of a green material with significant potential for strengthening and toughening, and has shown promising engineering applicability in crack resistance, frost resistance, erosion resistance, and dynamic response. Focusing on the issue of performance prediction for BFRC, this paper systematically reviews 15 representative studies from the perspectives of mechanical properties, durability, pore structure, and microscopic mechanisms. The results indicate that current research on BFRC performance prediction is still dominated by experiment-driven analysis and empirical modeling, mainly addressing sulfate attack depth, freeze–thaw damage attenuation, dynamic increase factors, and carbonation- and pore-evolution-related issues. Existing studies have substantially revealed the influence of fiber dosage, fiber length, environmental loading, and pore-structure parameters on material performance, and have preliminarily established prediction models for attack depth, dynamic response, and freeze–thaw damage fitting. However, current models still exhibit limitations in terms of variable-system consistency, micro–macro coupling characterization, generalization under multi-field environments, and data scale. Future studies should further promote standardized database construction, incorporation of microstructural characterization parameters, integration of mechanistic models with data-driven approaches, and long-term service prediction under multi-condition scenarios, so as to improve the scientific rigor and engineering applicability of BFRC performance prediction.

KEYWORDS: basalt fiber reinforced concrete; performance prediction; durability; pore structure; data-driven; empirical model

I. INTRODUCTION

Basalt fiber, due to its high strength, corrosion resistance, and environmental friendliness, has gradually become an important reinforcing material for cement-based composites. Compared with ordinary concrete, basalt fiber reinforced concrete exhibits clear advantages in crack suppression, toughness enhancement, and durability improvement, which makes it highly promising for applications in cold and arid regions, saline environments, and structures subjected to dynamic loading [1]. However, the performance of BFRC does not improve linearly with fiber incorporation; rather, it is jointly affected by multiple factors, including fiber length, fiber volume fraction, matrix composition, aggressive environment, temperature field, and loading conditions [2]. Therefore, relying solely on isolated experimental conclusions is insufficient for design and service-life evaluation under complex engineering scenarios, and establishing reliable performance prediction models has become an important research direction in this field.

From the existing literature, research on BFRC has gradually shifted from asking “whether it is effective” to exploring “under what conditions it is optimal” and “how predictable design can be achieved.” On the one hand, previous studies have revealed its deterioration patterns through experiments on sulfate attack, chloride attack, carbonation, freeze–thaw action, and thermal damage [3][4]; on the other hand, they have also begun to quantitatively describe performance evolution through attack-depth models, dynamic response models, and attenuation fitting models [5][6]. Overall, however, this field is still in the transitional stage from empirical models to data-driven models, and a truly generalizable prediction system for complex service conditions has not yet been established.

Accordingly, centering on the theme of “performance prediction,” this paper first sorts out the main performance indicators and key influencing factors of BFRC, then summarizes the construction paths, applicable boundaries, and existing problems of current prediction models, and further discusses the possible transition from empirical models to

data-driven approaches and from single-index fitting to multi-scale collaborative prediction, with the aim of providing reference for subsequent research and engineering applications.

II. MAIN TARGETS AND KEY VARIABLES IN BFRC PERFORMANCE PREDICTION

2.1 Mechanical properties as the most fundamental prediction targets

In BFRC research, compressive strength, splitting tensile strength, flexural strength, toughness, and dynamic increase factor are the most common performance indicators. Existing studies have shown that appropriate fiber incorporation can delay crack propagation, improve compressive toughness and deformation capacity, and alter the failure mode of concrete from brittle failure to more ductile failure [7]. From the perspective of uniaxial compression, fiber incorporation not only affects peak strength, but also significantly influences the process of energy storage and release, making compressive failure exhibit staged characteristics such as compaction, energy storage, local damage, and accelerated release of elastic energy [1]. Under dynamic loading conditions, fiber dosage, fiber length, and strain rate jointly affect dynamic compressive strength and damage evolution; therefore, dynamic mechanical response has also become an important target for prediction [5].

2.2 Durability as a key direction for engineering prediction

Compared with static strength, durability is more directly related to the long-term service safety of engineering structures. Current studies mainly focus on sulfate attack, combined-salt attack, salt freezing, chloride attack, carbonation, and thermal damage. Research has shown that basalt fibers can delay the progression of sulfate attack to a certain extent, causing the occurrence of strength peaks and attack characteristics to lag behind those in ordinary concrete [3]. In combined-salt environments, an appropriate amount of fiber can reduce the rate of both surface and internal deterioration, while the damage caused by combined salts is generally more severe than that caused by a single salt [8]. In chloride environments, the chloride diffusion coefficient of BFRC is lower than that of ordinary concrete, indicating that fibers exert a certain restraining effect on ion transport paths [4]. In addition, carbonation, freeze–thaw action, and elevated temperatures all induce pore-structure evolution and strength degradation, making the prediction of service life and deterioration rate equally important [9][10].

2.3 Key input variables affecting performance prediction

According to existing studies, the predictive variables for BFRC can mainly be classified into three categories. The first is fiber-related parameters, including volume fraction, length, and surface modification state. The second is environmental parameters, including sulfate concentration, chloride attack duration, carbonation duration, number of freeze–thaw cycles, and thermal damage temperature. The third is material and structural parameters, such as matrix strength grade, phosphogypsum content, and microscopic indicators including porosity, fractal dimension, and T2 spectrum characteristics [9][11]. It is particularly noteworthy that fiber dosage and fiber length generally exhibit an “optimal range” rather than a “more is better” effect. For example, some studies have found that a volume fraction of 0.2% yields the best performance in terms of erosion resistance or dynamic properties [5][12], while other studies have reported that 0.15% performs better under salt-freezing conditions [6]. In terms of length, 6 mm fibers show obvious advantages in frost resistance and pore control [2], whereas some studies have suggested that 12 mm fibers are more beneficial for certain mechanical indices [13]. This indicates that prediction models must be able to handle nonlinearity and context dependence among variables.

III. PERFORMANCE EVOLUTION PATTERNS AND THE BASIS FOR PREDICTION

3.1 Nonlinear effects of fiber parameters on basic mechanical properties

Multiple studies have shown that the strengthening effect of basalt fibers on concrete is not monotonic. When the dosage is too low, the crack-bridging effect is insufficient; when the dosage is too high, dispersion deteriorates, fiber agglomeration occurs, and interfacial defects increase, thereby weakening the reinforcing effect [1]. Under a fixed dosage, fiber length also has a significant influence. Excessive fiber length impairs workability and easily leads to fiber bundling, which is unfavorable for uniform distribution [2]. Therefore, fiber length and dosage together determine the bridging, restraining, and energy-dissipating capacities of the composite. For material prediction, this means that fiber parameters cannot be simply treated as linear gain terms; instead, piecewise or nonlinear relationship models should be established according to different service scenarios.

3.2 Stage-wise characteristics of performance degradation under environmental actions

Under attack and freeze–thaw environments, BFRC often exhibits a stage-wise pattern of “early stabilization or slight increase, followed by later decline.” Sulfate attack studies have shown that basalt fibers can delay the manifestation of attack damage and reduce the extent of strength loss [3]. During chloride attack, strength also shows a trend of increasing first and then decreasing, indicating that early attack products may temporarily fill local pores, whereas later deterioration is aggravated by crack propagation and ion accumulation [4]. Carbonation shows a similar pattern in which tensile strength first increases and then decreases, because early carbonate crystallization may temporarily densify the pore structure, while later expansion damage leads to strength reduction [10]. These staged characteristics suggest that performance prediction should not rely solely on conclusions drawn from a single age or a single environment, but should instead attach importance to the time dimension and the evolution process of damage.

3.3 Microstructural parameters as important intermediates for prediction

Pore structure and interfacial state are key intermediate variables linking external environment to macroscopic performance. Studies on salt freezing and thermal damage have shown that increased porosity, reduced fractal dimension, and an increase in large pores and cracks directly weaken the resistance of concrete to loads and aggressive environments [9][14]. Rapid carbonation tests have further demonstrated that porosity has a good exponential correlation with carbonation duration, and that BFRC consistently exhibits lower porosity and a slower carbonation rate than ordinary concrete [10]. Surface modification studies have shown that improving the fiber–matrix interfacial bonding can enhance mechanical strength and crack resistance [15]. Therefore, from the perspective of predictive modeling, using only strength or mass-loss indices remains insufficient. Incorporating porosity, pore-size distribution, fractal parameters, and interfacial bonding characterization into the variable system can significantly improve the explanatory power of prediction models.

IV. EXISTING TYPES OF PERFORMANCE PREDICTION MODELS FOR BFRC

4.1 Empirical prediction models based on attack processes

The most direct prediction path at present is to establish empirical relationship models around environmental deterioration processes. Sulfate attack studies have developed prediction models describing the relationship between concrete strength and attack depth, in order to characterize the internal link between attack development and mechanical degradation [3]. The advantage of such models lies in their explicit form, measurable parameters, and applicability to engineering estimation under specific aggressive environments. However, their limitations are equally evident: most of these models are established for specific strength grades, specific solution concentrations, and specific experimental regimes, resulting in limited transferability across environments.

4.2 Mechanical models based on dynamic response

Under dynamic loading, performance prediction places greater emphasis on rate effects and damage evolution. On the basis of analyzing the influence of basalt fiber dosage, fiber length, and strain rate, relevant studies have revised existing DIF models and established dynamic response models that account for fiber effects [5]. The value of such models lies in the fact that they not only describe variations in peak strength, but also incorporate the strengthening mechanism of the material under different loading rates into the model framework, thereby providing a basis for subsequent dynamic constitutive analysis. At the current stage, however, their application is still mainly limited to uniaxial compression conditions and has not yet adequately covered more complex cases such as impact, fatigue, and combined loading.

4.3 Freeze–thaw damage fitting models based on attenuation curves

Under freeze–thaw conditions, researchers often construct damage-evolution fitting models using indices such as mass-loss rate, relative dynamic elastic modulus, and compressive strength. Existing studies have established attenuation relationships between relative dynamic elastic modulus and mechanical indices based on experimental data, and have pointed out that quadratic polynomial fitting exhibits relatively high accuracy [6]. This approach has strong practical value for engineering, as it is suitable for preliminary material screening and service-life assessment. Nevertheless, such models are essentially statistical fitting models and are relatively insufficient in reflecting the mechanisms of pore-structure evolution, salt migration, and crack propagation.

4.4 Prediction research is still at the “experiment-driven” stage

Overall, current performance prediction for BFRC is still mainly based on experimental statistics. One type consists of strength–attack depth relationship models, another includes damage–time or damage–cycle number relationship models, and a third involves dynamic response correction models [3][5][6]. In addition, although some studies have not directly proposed prediction models, they have provided key patterns that can be used for future modeling. For example, phosphogypsum content, carbonation age, and carbonation depth have been shown to exhibit functional relationships [11]; different fiber lengths correspond to different porosity and frost-resistance behaviors [2]; and increasing temperature can lead to increased porosity and degradation of fractal characteristics [9]. These findings indicate that the field has already accumulated the basis for moving from empirical fitting to multivariable data modeling. However, truly meaningful machine-learning-oriented studies are still scarce, and at present it is more accurate to describe the field as being in the preliminary stage of transition toward data-driven modeling.

V. FROM EMPIRICAL MODELS TO DATA-DRIVEN APPROACHES: KEY PROBLEMS AND DIRECTIONS OF TRANSITION

5.1 Lack of a unified variable system constrains model generalization

Existing studies differ substantially in their choice of variables. Some emphasize fiber length and dosage [13], some focus on environmental factors and attack duration [12], while others start from microscopic parameters such as porosity and fractal dimension [9]. The inconsistency in variable definitions makes direct comparison across studies difficult and is also unfavorable for the construction of transferable datasets. If machine learning is to be further developed in this field, it is first necessary to establish relatively unified standards in terms of performance indices, input variables, and descriptions of experimental conditions.

5.2 Mechanistic information has not yet been fully transformed into model features

A large number of experimental studies have revealed mechanisms such as pore evolution, crack propagation, and interfacial bonding improvement through SEM, NMR, and CT techniques [14][15]. However, most of this microstructural information remains at the level of mechanistic interpretation and has not yet been systematically transformed into high-value features for modeling. In fact, parameters such as porosity, T2 spectral peak values, the proportion of micro- and mesopores, and fractal dimension can all serve as bridge variables linking microscopic damage with macroscopic performance [10]. How to embed these mechanism-based parameters into prediction models is a key issue for improving model interpretability in the future.

5.3 Prediction under multi-field coupled environments remains insufficient

Most existing studies focus on single or relatively well-defined conditions, such as sulfate attack, chloride attack, rapid carbonation, thermal damage, or freeze–thaw cycles [4][10]. In actual engineering practice, however, structures often face complex environments involving the combined effects of temperature, humidity, salts, and loading. Although some studies have already addressed combined-salt and salt-freezing conditions [8][14], the long-term service prediction under multi-field coupling remains relatively weak as a whole. The value of data-driven models in the future lies precisely in their ability to handle high-dimensional, multivariable, and nonlinear coupling problems.

5.4 A further step is needed from “fitting results” to “predictive design”

Current models are mostly used to explain existing experimental results, while their forward prediction capability for engineering design remains limited. For instance, there is still a lack of mature tools that can inversely determine the optimal fiber length, dosage, and matrix parameters according to target strength, service environment, and service-life requirements. Existing studies have revealed optimal ranges such as 0.2% dosage and 6 mm length [2][5], but these conclusions are mostly derived from specific experimental systems. A more valuable future direction is to build predictive frameworks that can be used for mix design, service-life assessment, and coordinated optimization of performance.

VI. FUTURE RESEARCH PROSPECTS

First, the construction of standardized BFRC databases should be promoted. Such databases should not only include conventional indices such as compressive, tensile, and flexural strengths, but should also synchronously record

environmental conditions, fiber parameters, matrix composition, and microstructural characterization results, so as to provide a stable foundation for training data-driven models.

Second, the integration of mechanistic models and data-driven models should be strengthened. For issues such as sulfate attack, carbonation, and freeze–thaw damage, existing studies have already revealed relatively clear damage paths and pore-evolution patterns [3][6]. Future research can build on this basis by coupling empirical formulas, transport theory, and damage mechanics frameworks with data-learning methods, thereby avoiding the poor interpretability associated with purely black-box models.

Third, multi-condition joint prediction should be developed for complex service scenarios. Current studies on high temperature, salt freezing, chloride attack, and carbonation have already provided a relatively good understanding under single conditions [4][9], but actual engineering practice requires comprehensive prediction models spanning different scenarios and timescales. This is both an academic challenge and an application scenario in which data-driven methods can demonstrate their advantages.

Finally, attention should be paid to constructing a closed loop of “performance prediction–material optimization–engineering application.” The ultimate purpose of prediction is not merely to fit observed phenomena, but to serve material design and engineering decision-making. With respect to issues such as fiber surface modification, incorporation of solid-waste components, and adaptation to service environments, future research may gradually establish intelligent optimization systems oriented toward target performance [11][15].

VII. CONCLUSIONS

Based on 15 representative references, this paper systematically reviews research on performance prediction of BFRC, and the following conclusions can be drawn.

First, the core targets of BFRC performance prediction mainly include static and dynamic mechanical properties, frost resistance, erosion resistance, carbonation resistance, and post-thermal-damage mechanical degradation, among which fiber dosage, fiber length, and environmental conditions are the most critical input factors [1][5].

Second, existing studies have already formed a certain foundation for prediction, mainly manifested in attack-depth prediction models, dynamic response models, and freeze–thaw damage fitting models. However, the field as a whole is still dominated by experimental statistics and empirical fitting, and truly data-driven research remains at an early stage [3][6].

Third, microscopic parameters such as porosity, fractal dimension, T2 spectrum characteristics, and interfacial bonding features are of important value for explaining macroscopic performance evolution, and constitute key bridges for constructing high-accuracy and interpretable prediction models in the future [9][10].

Fourth, future research should move from single-condition, single-index, and single-model studies toward multisource data, multi-field coupling, and mechanistic integration, so as to gradually establish intelligent BFRC prediction systems oriented toward engineering design and service-life evaluation.

VIII. FUNDING

This work was supported by Undergraduate Innovation and Entrepreneurship Training Plan Program of Hunan Province, China (S202411527053).

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