

Multiscale Analysis of Strengthening and Toughening Mechanisms of Basalt Fiber Reinforced Recycled Concrete

Zhixin LI, Ze LI, Peng ZHANG, Jun LIU, XinZhong WANG

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

ABSTRACT: Basalt fiber recycled concrete has attracted increasing attention as a sustainable construction material because it combines resource recycling with performance enhancement. To systematically clarify the strengthening and toughening mechanisms of basalt fiber in recycled concrete, this paper conducts a comprehensive analysis based on 15 representative studies from the perspectives of macroscopic mechanical response, microstructural optimization, crack propagation control, energy dissipation behavior, and performance evolution under coupled environmental actions. The results show that the improvement brought by basalt fiber is not limited to a simple increase in strength, but is achieved through a multiscale synergistic mechanism. At the macroscopic level, an appropriate fiber dosage can improve the compressive strength, tensile strength, crack resistance, and ductility of recycled concrete, although an obvious optimum dosage range exists. At the microscopic level, basalt fibers help optimize pore-size distribution, reduce porosity, and enhance the bonding condition of the interfacial transition zone, thereby improving the integrity of the cementitious matrix. At the mesoscale damage level, fibers delay crack initiation, propagation, and penetration through bridging, pull-out, deflection, and crack-arresting effects. In terms of energy evolution, basalt fibers reduce the release rate of elastic strain energy while increasing the energy storage limit and dissipation capacity, thus promoting a transition in failure mode from brittle instability to progressive energy-consuming damage. In addition, under complex environmental conditions such as freeze-thaw cycles, elevated temperature, and sulfate attack, basalt fibers still exhibit favorable effects in suppressing damage and maintaining toughness. Overall, the strengthening and toughening effect of basalt fiber on recycled concrete can be summarized as a continuous mechanism chain of “microstructure optimization–interface enhancement–crack control–energy dissipation”. Future studies should focus on long-term evolution under multi-field coupled service conditions and promote a shift from empirical optimization to data-driven material design.

KEYWORDS: basalt fiber; recycled concrete; strengthening and toughening mechanism; microstructure; energy dissipation; multiscale analysis

I. INTRODUCTION

Recycled concrete represents an important pathway for the resource utilization of construction and demolition waste. However, due to the presence of adhered old mortar within recycled aggregates, high porosity, and a weak interfacial transition zone (ITZ), its strength, crack resistance, durability, and long-term service performance are generally inferior to those of conventional concrete. Therefore, how to compensate for these inherent deficiencies while maintaining its green and low-carbon attributes has become a key issue in the engineering application of recycled concrete. Basalt fiber, characterized by high strength, excellent corrosion resistance, and strong crack-bridging capability, has been widely regarded as an effective reinforcement material for improving the brittleness and enhancing the toughness and service performance of recycled concrete.

Existing studies indicate that the improvement of recycled concrete by basalt fiber is not limited to a simple increase in strength. Instead, it acts throughout the entire process of crack initiation, propagation, and penetration, accompanied by multiple mechanisms such as pore structure optimization, enhancement of interfacial bonding, and changes in energy dissipation behavior. Zhou et al. demonstrated through energy evolution analysis that basalt fibers can reduce the release rate of elastic strain energy during compressive failure, increase the energy storage limit, and thus enhance the deformation resistance and stability of concrete [1]. This suggests that the role of basalt fibers goes beyond simple reinforcement and fundamentally reshapes the failure mechanism of the material.

Nevertheless, current research on basalt fiber reinforced recycled concrete still presents two major limitations. First, there is a lack of systematic integration among macroscopic mechanical behavior, mesoscale damage evolution, and microscopic structural characteristics, with many studies focusing only on improvements in individual performance indicators. Second, although considerable progress has been made in understanding strengthening and toughening behaviors under various environmental conditions, a clear multiscale mechanistic framework has yet to be established. Therefore, based on 15 representative studies, this paper systematically analyzes the strengthening and toughening mechanisms of basalt fiber reinforced recycled concrete from five aspects: macroscopic mechanical response, microstructural optimization, crack propagation control, energy dissipation characteristics, and performance evolution under coupled environmental conditions. The aim is to provide a theoretical basis for material design and performance prediction.

II. ENHANCEMENT OF MECHANICAL PROPERTIES OF RECYCLED CONCRETE BY BASALT FIBER

The most direct influence of basalt fibers on recycled concrete is reflected in the improvement of compressive strength, tensile strength, and deformation capacity. For compressive behavior, the incorporation of fibers generally exhibits a trend of “initial increase followed by decrease,” meaning that an appropriate fiber content enhances strength, while excessive fiber addition may reduce performance due to fiber agglomeration and poor dispersion. Studies on basalt fiber reinforced recycled concrete subjected to freeze-thaw cycles and high temperatures indicate that a fiber volume fraction of 0.15% provides the most significant improvement in compressive strength, splitting tensile strength, and stress–strain behavior [2]. This demonstrates that the strengthening effect of basalt fibers is characterized by a clear optimal dosage rather than a monotonic increase.

In addition to compressive performance, basalt fibers show a more pronounced improvement in tensile properties and ductility. Axial tensile tests reveal that with increasing fiber content, the initial cracking strength, tensile strength, initial cracking strain, and peak strain of recycled concrete first increase and then decrease, reaching their maximum at a fiber content of 0.3% [3]. This indicates that basalt fibers play a positive role in both the crack initiation stage and the post-peak deformation stage. From the perspective of failure characteristics, recycled concrete is inherently brittle, whereas basalt fibers, through crack-bridging and delay of strain localization, transform its failure mode from brittle fracture to a more ductile and gradual damage process.

In terms of crack resistance, basalt fibers exhibit significant engineering benefits. Studies on early-age cracking show that as the fiber content increases, the maximum crack width and total crack area per unit surface decrease continuously, indicating that fibers effectively suppress plastic shrinkage cracks and early microcrack formation [4]. This effect may not immediately result in a substantial increase in strength, but it plays a crucial role in delaying damage initiation, thereby improving long-term durability.

From the perspective of size effect, recycled concrete exhibits significant sensitivity to specimen dimensions under uniaxial compression. Research shows that with increasing height-to-thickness ratio, both peak stress and peak strain decrease significantly, mainly due to the weakening of confinement effects and the widening of crack propagation paths [5]. This implies that the strengthening effect of basalt fibers should not be understood solely in terms of intrinsic material properties, but rather in conjunction with structural scale and crack propagation behavior. In essence, the toughening effect introduced by fibers is fundamentally a regulation of crack propagation paths and failure modes.

III. MICROSTRUCTURAL MECHANISMS OF STRENGTHENING AND TOUGHENING BY BASALT FIBERS

The fundamental reason why basalt fibers can improve the performance of recycled concrete lies in their ability to modify the internal microstructure and interfacial load-transfer mechanisms. For recycled concrete, the presence of adhered old mortar, abundant microcracks, and coarsened pore structure are the key factors leading to performance deterioration. Therefore, the effectiveness of fiber reinforcement must ultimately be reflected at three levels: pores, interfaces, and cracks.

First, basalt fibers can optimize the pore structure and reduce the proportion of harmful pores. Studies on the pore structure of basalt fiber concrete under carbonation conditions have shown that, after fiber incorporation, both

carbonation depth and carbonation rate are lower than those of plain concrete. Moreover, the overall porosity is reduced, with a decrease in the proportion of large pores and cracks, and an increase in the proportion of micropores and mesopores [6]. These results indicate that basalt fibers not only play a bridging role under loading but also contribute to stabilizing the internal structure and suppressing pore coarsening during material formation and service.

Second, basalt fibers can improve the permeability resistance and corrosion resistance of recycled concrete, which is essentially related to pore structure and hydration product evolution. Research on chloride ion penetration has demonstrated that basalt fibers can optimize pore-size distribution by influencing the polymerization degree of C–S–H gel and the formation of CaCO₃. Under optimal conditions, the porosity is minimized, thereby significantly enhancing resistance to chloride ion penetration [7]. This suggests that fibers do not simply “fill” pores, but indirectly reconstruct transport pathways by promoting matrix densification.

Furthermore, the bonding condition at the fiber–matrix interface is critical for the effectiveness of strengthening and toughening. Studies on modified recycled concrete indicate that when the matrix structure is relatively loose, the bonding between fibers and the matrix is poor, limiting the reinforcement effect. However, with the synergistic incorporation of an appropriate amount of nano-SiO₂, the compactness of concrete increases, the Ca/Si ratio decreases, and the interfacial bonding between fibers and the matrix is significantly enhanced, leading to improved macroscopic compressive strength [8]. This phenomenon confirms that the reinforcing effect of basalt fibers relies on effective interfacial anchorage. Only when efficient load transfer is ensured at the interface can mechanisms such as fiber bridging, pull-out energy dissipation, and crack deflection be fully mobilized.

From the perspective of freeze–thaw-induced microdamage, SEM observations further support these conclusions. Studies on basalt fiber recycled concrete with iron tailings have shown that an appropriate fiber dosage can mitigate freeze–thaw damage, with the lowest strength loss observed at a fiber content of 0.1% and a length of 18 mm, corresponding to a more intact microstructure [9]. Similarly, investigations on short-cut basalt fiber concrete under freeze–thaw cycles indicate that such cycles promote internal crack propagation, whereas fiber incorporation reduces damage, with an optimal performance at a dosage of 0.4% [10]. These findings suggest that the microstructural role of basalt fibers can be summarized as follows: (1) stabilizing the pore structure and suppressing defect evolution; (2) strengthening interfacial bonding and improving stress transfer; and (3) bridging microcracks and delaying their propagation.

IV. CRACK CONTROL AND ENERGY DISSIPATION: CORE EXPRESSION OF TOUGHENING MECHANISMS

While pore optimization and interface enhancement explain “why strengthening occurs,” crack control and energy dissipation explain “why toughening is achieved.” The most significant contribution of basalt fibers to recycled concrete lies not only in increasing peak strength but also in altering the accumulation of damage before peak load and the evolution of failure after peak load.

Energy analysis under uniaxial compression shows that the failure process of basalt fiber concrete can be divided into four stages: compaction, energy storage, localized damage, and accelerated release of elastic energy. After fiber incorporation, the release rate of elastic energy decreases significantly, the energy threshold increases, and both the energy storage capacity and deformation resistance are improved [1]. This indicates that fibers do not prevent damage from occurring but delay instability, transforming rapid brittle failure into a more gradual energy-dissipating process.

Under freeze–thaw conditions, this energy-dissipation-based toughening mechanism becomes even more pronounced. Studies based on energy dissipation theory have shown that basalt fiber incorporation significantly enhances the strength, ductility, and energy absorption capacity of recycled concrete under both static and dynamic loading. Although the energy dissipation capacity decreases and mechanical damage increases with the number of freeze–thaw cycles, fibers can still effectively mitigate this deterioration [11]. Therefore, the essence of basalt fiber toughening lies in improving the conversion of input energy into dissipated energy through crack bridging and fiber pull-out mechanisms, thereby avoiding sudden brittle failure caused by concentrated energy release.

Under dynamic loading conditions, this effect becomes more evident. Studies on modified recycled concrete have shown that fibers improve dynamic compressive strength, peak strain, and specific energy absorption, while enhancing the integrity of specimens at failure [12]. This demonstrates that under high loading rates or impact conditions, fibers can effectively reduce local stress concentration caused by stress waves, making crack propagation more tortuous and increasing the energy dissipation path, thereby improving impact resistance.

Thus, the toughening effect of basalt fibers in recycled concrete should not be simply interpreted as “strength increase leading to toughness improvement.” Instead, it should be understood as a process in which fibers, through bridging, pull-out, deflection, and crack-arrest mechanisms, extend the damage evolution path, increase energy dissipation modes, and slow down post-peak instability, ultimately resulting in higher ductility, toughness, and damage tolerance.

V. EVOLUTION OF STRENGTHENING AND TOUGHENING MECHANISMS UNDER COUPLED ENVIRONMENTAL EFFECTS

In practical engineering applications, basalt fiber recycled concrete is often subjected to complex environments rather than single loading conditions, including freeze–thaw cycles, high temperatures, carbonation, chloride exposure, and sulfate attack. Therefore, evaluating its strengthening and toughening mechanisms requires consideration of whether these mechanisms remain effective under environmental disturbances and where their limitations lie.

Under freeze–thaw and high-temperature coupling conditions, the beneficial effects of basalt fibers remain evident but exhibit a clear optimal dosage effect. Studies have shown that after 25 freeze–thaw cycles, increasing the fiber volume fraction reduces mass loss and damage degree while improving the relative dynamic elastic modulus. After subsequent high-temperature exposure, a fiber content of 0.15% provides the most significant improvement in compressive and tensile properties [2]. This indicates that basalt fibers can both delay freeze–thaw-induced internal damage accumulation and maintain residual load-bearing capacity after high-temperature exposure, although their effectiveness is constrained by fiber distribution and matrix integrity.

Under high-temperature water-cooling conditions, the compressive damage process of basalt fiber recycled concrete can be divided into three stages: compaction and crack initiation, crack propagation and coalescence, and post-peak failure. The cumulative acoustic emission ringing counts differ significantly across these stages [13]. This suggests that rapid cooling after high temperatures intensifies internal thermal stresses and crack development, whereas fiber incorporation leads to a more staged and identifiable damage evolution, providing a basis for residual performance assessment.

In sulfate attack environments, fiber incorporation significantly enhances peak strain and deformation capacity of recycled concrete, while its effect on elastic modulus is limited [14]. This indicates that under chemical erosion, basalt fibers contribute more to “toughening” than to “stiffening.” In other words, even when the interfacial transition zone is degraded by corrosion, fibers can still maintain a certain level of toughness by improving post-peak deformation and delaying crack penetration.

Further studies on freeze–thaw-induced mechanical properties show that, after 100 cycles, fiber-reinforced recycled concrete can exhibit approximately 16% higher compressive strength, with only a slight reduction in elastic modulus and little change in peak strain, demonstrating good compressive performance and ductility. Meanwhile, the effect of freeze–thaw cycles on the interfacial transition zone is identified as a key factor determining failure modes [15]. This finding is consistent with the interface-dominated mechanism discussed earlier: environmental loading primarily damages weak interfaces in recycled concrete, and the core value of basalt fibers lies in compensating for and regulating these weak regions.

VI. CONCLUSIONS AND FUTURE PERSPECTIVES

Based on the above analysis, the strengthening and toughening effect of basalt fibers on recycled concrete exhibits a distinct multiscale characteristic and is not solely dependent on the improvement of a single mechanical parameter. Instead, it is achieved through a continuous mechanism chain of “microstructure optimization–interface enhancement–crack control–energy dissipation.”

First, basalt fibers can effectively improve the compressive strength, tensile strength, crack resistance, and ductility of recycled concrete, but their effectiveness typically exhibits an “optimal dosage” characteristic, with excessive fiber content potentially reducing performance due to poor dispersion and fiber clustering [3].

Second, at the microscopic level, basalt fibers can reduce porosity, optimize pore-size distribution, decrease the proportion of large pores and cracks, and enhance interfacial bonding, thereby improving matrix integrity [6]. This is particularly important for recycled concrete, whose inherent defects mainly lie in pore coarsening and weak interfaces.

Third, at the mesoscale damage level, basalt fibers significantly alter the evolution process from crack initiation to failure by bridging microcracks, inhibiting crack propagation, and delaying crack penetration [4]. This crack-control capability is the direct source of their toughening effect.

Fourth, in terms of energy evolution, fiber incorporation increases the energy storage capacity and dissipation capability of recycled concrete, reduces the instantaneous release rate of elastic energy, and transforms failure from brittle instability to progressive energy-dissipating damage [1]. This is a key advantage of basalt fibers compared with purely rigid fillers.

Fifth, under complex environmental conditions, basalt fibers generally maintain stable performance improvement, particularly in resisting freeze–thaw damage, high-temperature degradation, and chemical attack, although their effectiveness is influenced by environmental severity, interface degradation, and fiber dosage matching [14].

Future research should focus on three aspects: (1) detailed multiscale characterization of the synergistic interaction among recycled aggregates, cement matrix, and fibers; (2) long-term evolution mechanisms under multi-field coupled service conditions such as freeze–thaw, corrosion, and loading; and (3) establishing relationships among microstructural parameters, mechanical properties, and durability indicators, thereby promoting a transition from empirical optimization to data-driven design of basalt fiber recycled concrete. Overall, basalt fibers provide a reliable pathway for performance enhancement of recycled concrete, and the key to their widespread engineering application lies in integrating existing fragmented findings into a unified, predictable, and design-oriented strengthening and toughening framework.

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