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# **Mechanical Performance and Structural Evolution of Recycled Powder Mortar Reinforced with Basalt Fibers**

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**ABSTRACT:** To evaluate the influence of basalt fiber (BF) on the mechanical performance of recycled powder (RP) mortar, BF was incorporated at 0%, 0.10%, 0.15%, and 0.20%, and the 28-day flexural and compressive strengths were tested. Macroscopic fracture observation and SEM analysis were conducted to clarify the reinforcement mechanism. Without BF, mechanical properties decreased with increasing RP replacement ratio. The addition of BF significantly improved strength at all replacement levels, with 0.15% identified as the optimal dosage. At 30% RP replacement, flexural and compressive strengths increased by 16.0% and 35.7%, respectively, effectively mitigating the strength loss caused by high RP content. SEM results showed that RP increased pore and microcrack formation, while BF restrained crack propagation through bridging and deflection effects. Overall, appropriate BF incorporation effectively enhances the mechanical performance of RP mortar.

**KEYWORDS:** Recycled powder, Basalt fiber, Mechanical properties, Cement mortar, Microstructure.

## **I. INTRODUCTION**

With the continuous increase in construction waste generation, the recycling and resource utilization of waste concrete have become an important research focus in the field of construction materials [1–3]. Recycled powder, obtained from crushed and ground waste concrete, has attracted growing attention due to its wide availability, low cost, and potential environmental benefits [4,5]. Previous studies have shown that recycled powder can partially replace cement in cementitious systems and influence the rheological behavior and early hydration process of cement paste [6–8]. However, owing to its relatively low reactivity, irregular particle morphology, and weak interfacial transition zone (ITZ) structure, high replacement levels often result in significant reductions in compressive and flexural strengths [9–11], thereby limiting its practical engineering application.

To compensate for the strength loss caused by recycled powder substitution, fiber reinforcement has been considered an effective modification approach [12,13]. Basalt fiber, as a novel inorganic fiber material, exhibits high strength, excellent corrosion resistance, and good compatibility with cement-based materials. Previous research has demonstrated that basalt fibers can improve the toughness and crack resistance of cementitious composites through crack-bridging and microcrack inhibition mechanisms [14–16]. Moreover, the reinforcing effect of fibers tends to be more pronounced in relatively weakened matrix systems [17]. Nevertheless, existing studies mainly focus on conventional concrete or single-variable analyses, and systematic investigations on the synergistic effects of recycled powder and basalt fiber remain limited. In particular, quantitative differences in fiber enhancement efficiency under varying replacement ratios have not yet been clearly established.

In addition, quantitative evaluation of strength degradation at elevated recycled powder contents, as well as determination of the optimal fiber dosage range, still requires further experimental validation. The correlation between macroscopic mechanical performance and microstructural evolution also needs to be clarified through multi-scale analysis.

Therefore, this study prepared mortar with recycled powder partially replacing cement and incorporated different basalt fiber dosages. The effects on 28-day flexural and compressive strengths were systematically investigated, and the reinforcement mechanisms were analyzed through macroscopic fracture observation and scanning electron microscopy (SEM). The findings provide experimental evidence and theoretical support for the high-value utilization of recycled powder and the design of fiber-reinforced cementitious composites.

## II. METHODOLOGY

### (1) Materials and Preparation

The raw materials used in this study included ISO standard sand, ordinary Portland cement, recycled powder (RP), basalt fiber (BF), and mixing water. The ISO standard sand was supplied by a certified manufacturer to ensure uniform particle grading and compliance with GB/T 17671 requirements. Tap water was used for mixing, and its quality satisfied the standard requirements for cement-based materials. Ordinary Portland cement (P·O 42.5) was adopted as the primary binder due to its stable performance and widespread engineering application.

The recycled powder was obtained from waste concrete specimens produced in the laboratory. The original concrete had a compressive strength grade of C30. After mechanical crushing and sieving, the material was further ground to achieve a particle size smaller than 75  $\mu\text{m}$ . The finely processed recycled powder was then used to partially replace cement in the mortar mixtures. Compared with cement particles, the recycled powder exhibited irregular morphology and relatively rough surfaces, which may influence the packing density and interfacial characteristics of the matrix.

The basalt fiber was a chopped fiber product supplied by Zhejiang Shijin Basalt Fiber Co., Ltd. The fibers had a nominal diameter of approximately 17  $\mu\text{m}$  and a length of 12 mm. The high tensile strength, good alkali resistance, and compatibility with cementitious matrices make basalt fiber suitable for reinforcing mortar systems. The fibers were uniformly dispersed in short-cut form prior to mixing to reduce the risk of agglomeration.

Figure 1 illustrates the morphology of the basalt fiber and recycled powder used in this study. The basalt fibers appear as uniformly distributed short filaments, while the recycled powder particles are fine and relatively homogeneous in size. The combined use of these materials provided a stable and controllable basis for subsequent mortar preparation and performance evaluation.



Fig. 1. Experimental materials (a) Basalt fiber (b) Recycled powder.

### (2) Mix Proportion Design

A total of 16 mortar mixtures were designed and cured for 28 days. Recycled powder (RP) was used to partially replace cement and combined with different dosages of basalt fiber (BF). The mortar strength grade was controlled as M30 in accordance with GB/T 17671—2021 (ISO method). The water-to-binder ratio (w/b) was fixed at 0.5 for all mixtures.

The reference mixture consisted of 225 mL water, 450 g cement, and 1350 g standard sand. RP replaced cement at mass fractions of 10%, 20%, and 30%, corresponding to cement contents of 405 g, 360 g, and 315 g, respectively. BF was incorporated at 0%, 0.10%, 0.15%, and 0.20% to form different combination schemes. (The experimental design is shown in Table 1.)

Specimens with dimensions of 40 mm × 40 mm × 160 mm were prepared by standard mixing and vibration compaction. After casting, the specimens were kept in molds for 24 h before demolding and subsequently cured under standard conditions (20 ± 2 °C, relative humidity >95%) until 28 days. Mechanical tests were conducted at the specified curing age.

Table 1 Orthogonal experimental design of recycled micronized mortar.

Group No.	Fiber content (vol.%)	Recycled powder replacement ratio (%)	Cement (g)	Water-to-binder ratio (w/b)	Standard sand (g)	Water (g)
1	0	0	450	0.5	1350	225
2	0.1	10	405	0.5	1350	225
3	0.15	20	360	0.5	1350	225
4	0.20	30	315	0.5	1350	225

### (3) Mechanical Testing of Mortar

The mechanical properties were determined in accordance with GB/T 17671—1999. Specimens were cast in stainless steel triple molds and compacted on a vibration table operating at 50 Hz with a vibration amplitude of 0.5 mm.

After 24 h of curing at 20 ± 1 °C and relative humidity ≥95%, specimens were demolded and further cured to 28 days. Flexural strength was measured using a WAW-1000 universal testing machine under three-point bending with a span of 100 mm and a loading rate of 50 N/s. The fractured halves were then subjected to compressive strength testing at a loading rate of 2.4 kN/s with a loading area of 40 mm × 40 mm.

Microstructural characteristics were analyzed using a SEM5000 scanning electron microscope (the experimental equipment is shown in Figure 2).

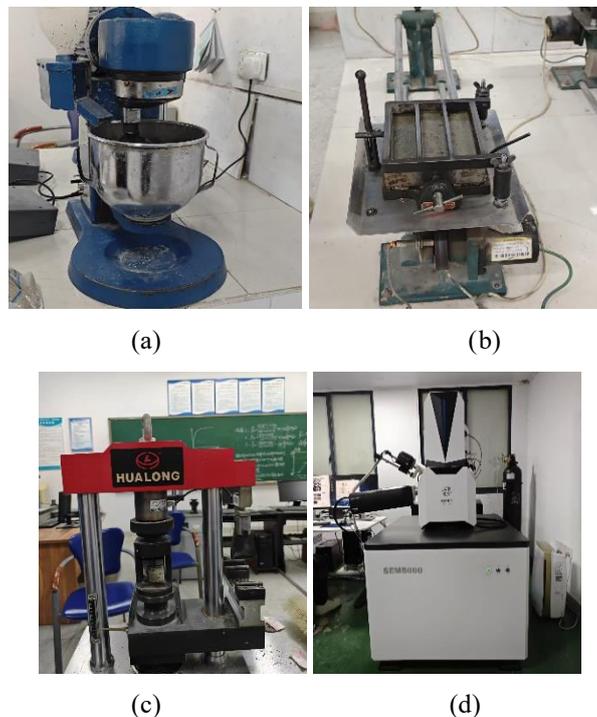


Fig. 2. Experimental equipment (a) Mixer (b) Vibration table (c) Computer-controlled electro-hydraulic servo universal testing machine (d) SEM5000 scanning electron microscope.

### III. EXPERIMENTAL RESULTS

#### (1) Flexural Strength Analysis

Figure 3 presents the development of flexural strength at 28 days. In the absence of basalt fiber (BF-0), flexural strength decreased significantly with increasing recycled powder (RP) replacement ratio. When the replacement level increased from 0% to 30%, the flexural strength declined from 6.7 MPa to 5.0 MPa, corresponding to a reduction of 25.4%. This indicates that a high RP content weakens the crack resistance of the matrix, likely due to reduced compactness and deterioration of the interfacial transition zone. With the incorporation of BF, the flexural strength at all replacement levels was markedly improved [18,19], and the declining trend was effectively mitigated, demonstrating that BF can compensate for the adverse effects induced by RP substitution.

In terms of enhancement magnitude, BF exhibited a consistent toughening effect across different replacement ratios. At 0% RP replacement, the flexural strengths of the BF-0.10%, BF-0.15%, and BF-0.20% groups were 7.5, 7.6, and 7.2 MPa, representing increases of 11.9%, 13.4%, and 7.5%, respectively, compared with BF-0. Under 10%, 20%, and 30% RP replacement, the BF-0.15% group consistently achieved the highest values (6.8, 6.3, and 5.8 MPa), corresponding to improvements of 9.7%, 10.5%, and 16.0%, respectively. Notably, the relative enhancement became more pronounced as the RP replacement ratio increased, particularly at 30%, suggesting that the crack-bridging effect of fibers is more effective in relatively weakened matrices.

Further comparison indicates that 0.15% is the optimal BF dosage for flexural strength enhancement. When the dosage increased to 0.20%, a slight strength reduction was observed (e.g., from 5.8 MPa to 5.7 MPa at 30% RP replacement), which may be attributed to fiber agglomeration or reduced dispersion efficiency. Overall, for every 10% increase in RP replacement, the average flexural strength decreased by approximately 0.6 MPa in the BF-0 group, whereas the reduction was only about 0.3 MPa in the BF-0.15% group, representing a nearly 50% decrease in the degradation rate. These results confirm the synergistic enhancement effect of basalt fiber in RP mortar systems.

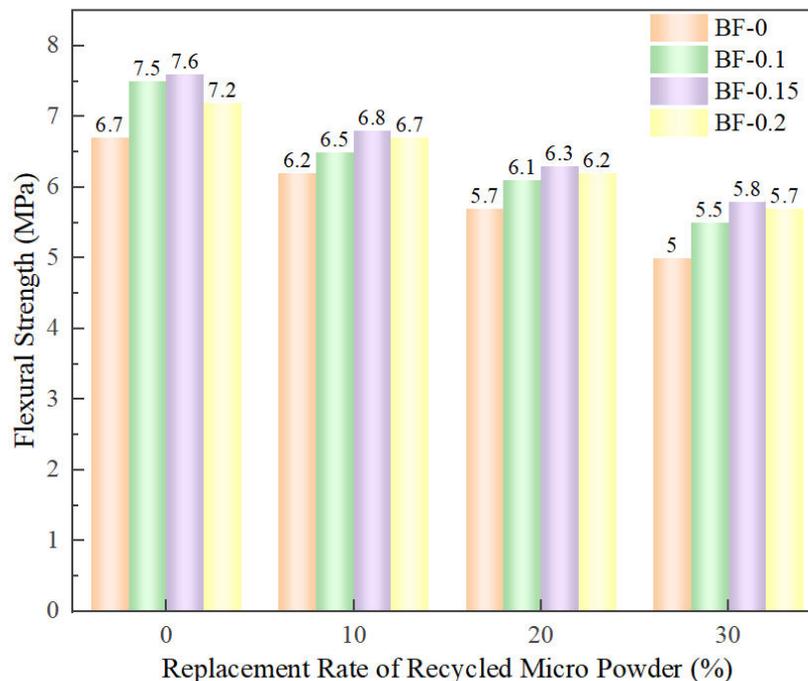


Fig. 3. Influence of basalt fiber content on the flexural strength of recycled powder (RP) mortar at 28 days.

(2) Compressive Strength Analysis

As shown in Figure 4, in the absence of basalt fiber (BF-0), compressive strength decreased markedly with increasing recycled powder (RP) replacement ratio. When the replacement level increased from 0% to 30%, the compressive strength declined from 48.0 MPa to 28.6 MPa, corresponding to a reduction of 40.4%. This significant strength loss can be attributed to the relatively low reactivity of RP, unfavorable particle grading, and deterioration of the interfacial transition zone. After incorporating BF, compressive strength at all replacement levels was significantly improved [20,21], and the rate of strength reduction was effectively mitigated, indicating that BF partially compensates for the structural weakening caused by RP substitution.

In terms of enhancement magnitude, BF exhibited a stable and pronounced strengthening effect across all replacement ratios. At 0% RP replacement, the compressive strengths of the BF-0.10%, BF-0.15%, and BF-0.20% groups were 54.3, 55.5, and 49.3 MPa, representing increases of 13.1%, 15.6%, and 2.7%, respectively, compared with BF-0, with 0.15% showing the maximum value. At 10%, 20%, and 30% RP replacement, the compressive strength of the BF-0.15% group reached 46.3, 42.1, and 38.8 MPa, corresponding to improvements of 32.3%, 30.7%, and 35.7%, respectively, compared with the non-fiber groups. Notably, the relative enhancement became more pronounced at higher RP replacement levels, suggesting that the crack-arresting and microcrack-bridging effects of BF are more effective in weakened matrices.

Further comparison indicates that 0.15% is the optimal BF dosage for compressive strength enhancement. When the dosage increased to 0.20%, a slight reduction in strength was observed (e.g., from 55.5 MPa to 49.3 MPa at 0% RP and from 38.8 MPa to 37.2 MPa at 30% RP), which may be attributed to fiber agglomeration or increased porosity. Overall, for every 10% increase in RP replacement, the average compressive strength decreased by approximately 6.5 MPa in the BF-0 group, whereas the reduction was about 5.6 MPa in the BF-0.15% group, indicating a slower degradation rate. These findings demonstrate a clear synergistic strengthening effect of basalt fiber in RP mortar systems.

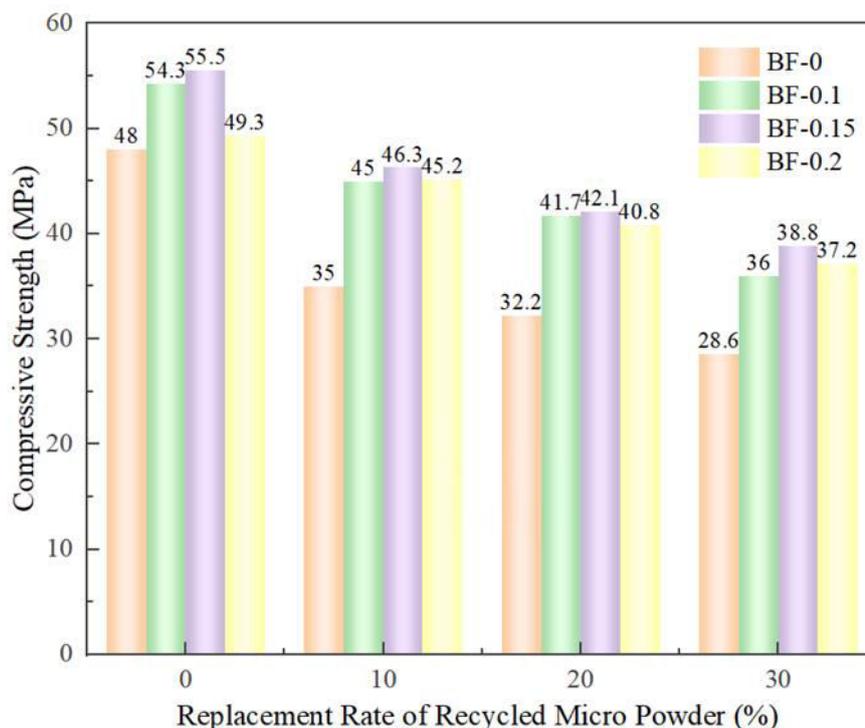


Fig. 4. Influence of basalt fiber content on the compressive strength of recycled powder (RP) mortar at 28 days.

### (3) Macroscopic Analysis of Recycled Powder Mortar

As shown in Figure 5(a)–(c), significant differences in fracture morphology were observed among the mixtures. The ordinary cement mortar (M) exhibited a relatively smooth and dense fracture surface with only a small number of dispersed pores, indicating good structural continuity.

After incorporating recycled powder (RPM), the number and size of pores increased noticeably, and localized void concentration areas were observed. The irregular morphology and rough surface of RP particles, together with their relatively high water absorption capacity, may induce local fluctuations in the effective water-to-binder ratio, resulting in loose regions and potential defects within the matrix. These defects can act as crack initiation sites under loading, thereby reducing the overall compactness and integrity of the material.

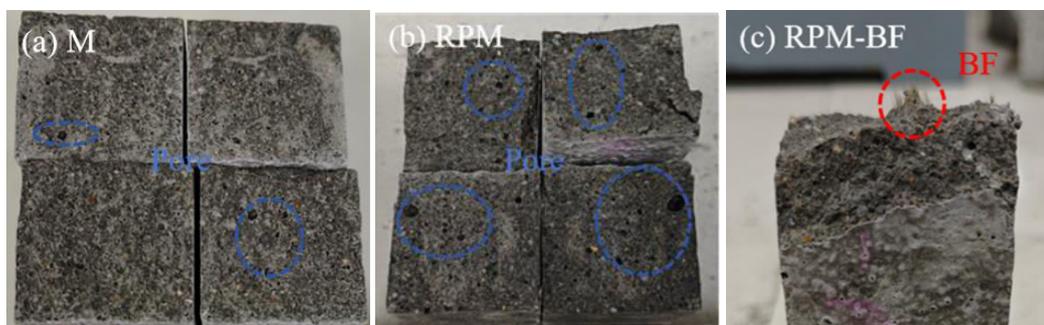


Fig. 5. Macroscopic fracture characteristics of the mortar specimens.

With the addition of basalt fiber (RPM-BF), exposed fibers and clear crack-bridging phenomena were observed on the fracture surface. The fibers were able to span cracks, transfer tensile stress, and delay crack propagation, thereby improving the failure mode. Although some pores remained in the matrix, the reinforcing effect of BF significantly enhanced structural integrity and crack resistance.

Overall, the incorporation of RP increased pore content, whereas BF optimized crack evolution through bridging effects. The macroscopic observations are consistent with the mechanical performance results.

### (4) Microstructural Mechanism Analysis of Recycled Powder Mortar

As shown in Figure 6(a), the ordinary cement mortar (M) exhibited a relatively dense microstructure with uniformly distributed hydration products. The C–S–H gel presented an interwoven flocculent morphology, and crystals were tightly bonded with few pores observed, indicating adequate hydration and good structural continuity.

After incorporating recycled powder (RPM), as shown in Figure 6(b), an increased number of microcracks and pores were observed within the matrix, and localized loose regions appeared. The irregular morphology and rough surface of RP particles, along with possible internal micro-defects, may cause non-uniform water distribution due to their water absorption characteristics. This can weaken the interfacial transition zone and lead to the formation of microcracks, which serve as initiation sites for crack propagation and contribute to strength reduction and brittle failure.

With the addition of basalt fiber (RPM-BF), as illustrated in Figure 6(c), fibers were well embedded in the matrix without obvious large-scale debonding. The fibers bridged microcracks, transferred tensile stress during crack propagation, and dissipated energy through pull-out mechanisms. These effects delayed crack coalescence and induced crack deflection and branching, thereby improving the failure behavior.

Overall, the incorporation of RP increased microcracks and pore content in the matrix, whereas BF effectively restrained crack propagation through bridging and energy dissipation mechanisms. The microstructural observations are consistent with the macroscopic mechanical performance.

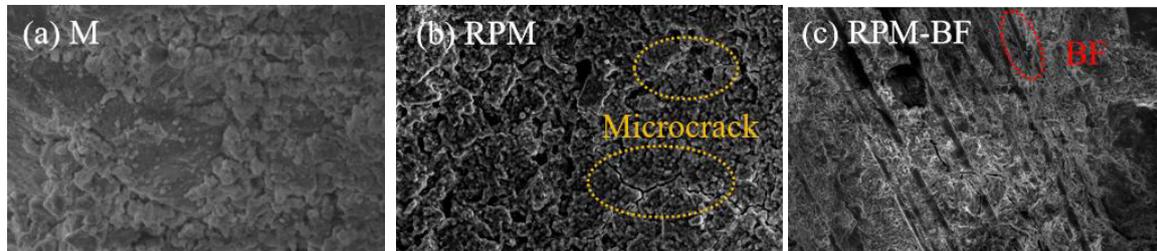


Fig. 6. SEM images of different mortar specimens.

#### IV. CONCLUSION

- (1) The incorporation of recycled powder (RP) significantly influenced the mechanical performance of mortar. In the absence of basalt fiber (BF), both flexural and compressive strengths decreased continuously with increasing RP replacement ratio. When the replacement level increased from 0% to 30%, flexural strength decreased by approximately 25% and compressive strength by about 40%, indicating that high RP content weakens the load-bearing capacity of the matrix.
- (2) The addition of BF markedly improved the mechanical properties of RP mortar. At all replacement levels, BF exhibited a stable strengthening effect, which became more pronounced in relatively weakened matrices. Among the investigated dosages, 0.15% BF provided the optimal overall enhancement, effectively increasing both flexural and compressive strengths and reducing the strength degradation induced by higher RP replacement.
- (3) Macroscopic fracture observations and SEM analysis revealed that RP incorporation increased pore content and microcrack formation, leading to reduced matrix compactness. In contrast, BF restrained crack propagation through bridging mechanisms, altered crack development paths, and improved deformation compatibility and crack resistance.
- (4) Overall, an appropriate amount of BF can partially compensate for the structural weakening caused by RP substitution. A clear synergistic enhancement effect was observed within a suitable dosage range, with 0.15% identified as the optimal fiber content in this study.

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