Effect of Basalt Fiber on Chloride Ion Penetration Resistance of Recycled Concrete for High-Altitude Applications

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Abstract

Recycled coarse aggregate (RCA) concrete suffers from inferior chloride penetration resistance due to its high porosity, a problem intensified by the low air pressure and dry climate of high-altitude regions such as Kunming, China. Although basalt fiber (BF) has been shown to improve concrete performance, its combined micro-macro effects on RCA concrete under high-altitude conditions remain unquantified. This study experimentally investigated the mechanical and chloride penetration properties of concrete with varying RCA replacement ratios (0–60%) and BF volume fractions (0–0.4%), using Mercury Intrusion Porosimetry (MIP) to reveal the microstructural mechanisms. Results showed a "V-shaped" trend in water absorption and electric flux with increasing BF content. The 0.3% BF dosage yielded the highest mechanical enhancement (27.6% increase in splitting tensile strength), while the 0.2% BF combined with 50% RCA achieved the lowest electric flux of 3135.5 C—outperforming even the natural aggregate control. MIP analysis confirmed that 0.2% BF refined the pore structure, increasing harmless pores (<100 nm) to 68.52% and severing capillary pathways. From a practical engineering perspective, these results demonstrate that low-dosage BF reinforcement can effectively compensate for the durability loss of RCA concrete in high-altitude construction, providing a viable and sustainable mix design strategy for infrastructure in such demanding environments.

Keywords: High-altitude areas; Basalt fiber; Recycled concrete; Chloride penetration; Electric flux; Mercury intrusion porosimetry

Introduction

Rapid urbanization had led to a massive accumulation of construction and demolition waste. Utilizing recycled coarse aggregate (RCA) in concrete aligned with the global goals of carbon peak and carbon neutrality (Xiao, 2021). However, RCA typically exhibited higher water absorption and a larger crushing index than natural aggregate due to the presence of micro-cracks and old mortar residues. These inherent defects significantly impaired the chloride penetration resistance of recycled concrete, which was a primary cause of durability failure in reinforced structures (Chen et al., 2021; Yan, 2013).

In high-altitude areas like Kunming (elevation 1891 m), the low atmospheric pressure and dry climate accelerated early moisture loss, further exacerbating shrinkage cracking and porosity in concrete (Cao et al., 2019). To mitigate these issues, fiber reinforcement had been widely adopted. Basalt fiber (BF), an eco-friendly inorganic material, offered high tensile strength, excellent corrosion resistance, and a thermal expansion coefficient similar to concrete (Wu, 2020). Previous studies demonstrated that BF could bridge micro-cracks and improve the mechanical strength of RCA concrete (Dong et al., 2020; Li et al., 2017). Nevertheless, most existing research had been conducted under normal temperature and pressure conditions. The synergistic effect of BF and RCA on chloride penetration resistance under high-altitude constraints had not been systematically investigated (Liu et al., 2021; Xie et al., 2021).

Despite these advances, a critical research gap persists: no existing study has systematically quantified the synergistic effect of BF dosage and RCA replacement ratio on chloride penetration resistance under the unique environmental constraints of high-altitude regions, nor has the underlying pore-refinement mechanism been elucidated using microstructural analysis techniques such as MIP. To address this gap, this study aimed to optimize the mix design of BF-reinforced recycled concrete for high-altitude environments. The specific objectives were to: (1) evaluate the macroscopic effects of BF dosage and RCA replacement on physical and mechanical properties; (2) quantify the chloride penetration resistance (via electric flux) under varying mix proportions; and (3) elucidate the microstructural pore-refinement mechanism using Mercury Intrusion Porosimetry (MIP) (Shi & Yuan, 2018; Ding et al., 2020).

Materials and Methods

1. General

This study adopted a laboratory experimental approach. The experimental program was designed following a comparative group approach, with one control group and multiple BF-reinforced groups tested under standardized conditions. All mechanical property tests complied with the Chinese national standard GB/T 50081-2019 "Standard for Test Methods of Mechanical Properties of Ordinary Concrete" for specimen preparation, curing, and testing procedures. Chloride penetration resistance was evaluated according to GB/T 50082-2009. Adherence to both national and international standards ensured the reliability, reproducibility, and cross-study comparability of all test results.

2. Materials

The materials used in this study comprised cementitious materials, aggregates, basalt fiber, and chemical admixtures. The experiment utilized P·O 42.5 grade Portland cement. The natural coarse aggregate was continuous graded crushed stone (5–20 mm), while the RCA was sourced from demolished residential buildings in Kunming, classified as Class II aggregate with a water absorption of 12% and a crushing index of 20%. Natural medium sand with a fineness modulus of 2.3 was used. The basalt fiber (Sichuan Aerospace Tuoxin) had a length of 18 mm, a diameter of 17.4 μm, and a tensile strength of 2500 MPa. A polycarboxylate superplasticizer was added to adjust workability. To compensate for the bubble loss caused by low air pressure at high altitudes, an air-entraining agent was specifically adjusted in the mixing water. Complete specifications are provided in Table 1.

Table 1. Specifications and Key Properties of Materials Used in the Experimental Program

Material	Specification & Source	Key Performance Parameters
Cement	P·O 42.5R	3-day compressive strength ≥ 22.5 MPa
Natural Coarse Aggregate	5~20 mm continuous gradation	Apparent density 2.55 g/cm³; crushing index 14%
Recycled Coarse Aggregate	Class II, from Kunming demolition waste	Apparent density 2.36 g/cm³; water absorption 12%; crushing index 20%
Natural Sand	Medium sand	Fineness modulus 2.3; apparent density 2.46 g/cm³
Basalt Fiber	Sichuan Aerospace Tuoxin	Diameter 17.4 μm; length 18 mm; tensile strength 2500 MPa
Water-Reducing Agent	Polycarboxylate superplasticizer	Dosage 2 kg/m³

3. Mix Proportion Design

Based on a target strength grade of C30 (water-to-binder ratio of 0.48), four BF volume fractions (0%, 0.2%, 0.3%, 0.4%) and four RCA mass replacement ratios (0%, 40%, 50%, 60%) were designed. The BF dosages were selected based on the findings of Dong et al. (2020) and Li et al. (2017), who reported that BF volume fractions within the 0.1–0.5% range yielded optimal crack-bridging effects without significant agglomeration. The RCA replacement ratios of 40–60% were chosen to represent practical engineering scenarios where moderate-to-high recycled content is economically desirable while remaining within the range where durability modifications are most critical (Chen et al., 2021). A normal aggregate concrete (NAC) group without BF was cast as the control. A two-stage mixing method was adopted to prevent BF agglomeration. BF and fine aggregates were dry-mixed for 30 s, followed by the addition of coarse aggregates, cement, and water for another 280 s. Specimens were cast, vibrated, and cured in a standard room (20±2 °C, RH≥95%) for 28 days. The detailed mix proportions for all groups are presented in Table 2.

Table 2. Base Mix Proportions of the Concrete Specimens (kg/m³)

Group	Cement	Water	Natural Sand	Natural Agg.	Recycled Agg.	WRA
NAC	417	221	643	1194	0	2.0
R40	417	221	643	717	478	2.0
R50	417	221	643	597	597	2.0
R60	417	221	643	478	717	2.0

Note: Basalt fibers were added additionally according to the volume fractions of 0%, 0.2%, 0.3%, and 0.4% of the total concrete volume.

4. Experimental Program

4.1. Specimen Preparation and Testing Methods

Water absorption was tested after drying the specimens at 60 °C and immersing them in distilled water for 48 hours. Compressive and splitting tensile strengths were evaluated using a universal testing machine in accordance with GB/T 50081-2019. For chloride penetration, the 6-hour electric flux test was conducted using an NJ-AR tester according to GB/T 50082-2009. Microstructural pore characteristics were analyzed using an Anton Paar PoreMaster 60 MIP analyzer on paste samples arrested from hydration via anhydrous ethanol (Shi & Yuan, 2018).

Results and Discussion

1. Physical and Mechanical Properties

The inclusion of RCA inherently increased the water absorption of concrete, as presented in Table 3. For the unreinforced RCA groups, absorption rose from 4.52% (control) to 6.23% at a 50% replacement ratio due to the old mortar's high porosity. However, the addition of BF exhibited a "V-shaped" control effect. At 0.2% BF, water absorption reached its minimum (5.42% for the 50% RCA group), representing a 13.0% reduction compared to the unreinforced counterpart. Excessive BF (0.4%) caused fiber agglomeration, introducing new irregular voids and increasing absorption (Dong et al., 2020).

Table 3. Results of Water Absorption of Recycled Concrete under Different Mix Proportions

BF	RCA=0%	RCA=40%	RCA=50%	RCA=60%
0%	4.52%	5.85%	6.23%	6.81%
0.2%	4.15%	5.21%	5.42%	5.95%
0.3%	4.28%	5.35%	5.61%	6.12%
0.4%	4.45%	5.58%	5.85%	6.43%

Mechanically, BF provided significant compensation for the strength loss caused by RCA, which was summarized in Table 4 (compressive strength) and Table 5 (splitting tensile strength). The optimal mechanical enhancement was observed at a 0.3% BF dosage. For the 50% RCA group, the splitting tensile strength surged from 3.12 MPa (0% BF) to 3.98 MPa (0.3% BF), achieving a remarkable 27.6% increment. This magnitude of improvement is consistent with the findings of Dong et al. (2020), who reported a 20–30% tensile strength gain for BF-reinforced recycled concrete at similar fiber dosages under standard curing conditions. Li et al. (2017) similarly observed that BF at 0.2–0.3% effectively enhanced the mechanical properties of RCA concrete through crack-bridging mechanisms. The high-modulus fibers effectively bridged the Interfacial Transition Zone (ITZ) between the old and new mortar, transforming the failure mode from brittle sudden rupture to a ductile "cracked but not broken" state. Notably, Liu et al. (2021) confirmed that BF improved uniaxial tensile performance of RCA concrete, supporting the toughening effect observed in the present study. The slightly higher enhancement observed in this study compared to those under normal conditions may be attributed to the increased role of fiber bridging in mitigating the additional micro-cracking caused by high-altitude drying shrinkage (Cao et al., 2019).

Table 4. Compressive Strength of Recycled Concrete under Different Mix Proportions at 28 Days (MPa)

BF	RCA=0%	RCA=40%	RCA=50%	RCA=60%
0%	48.5	43.2	41.6	38.5
0.2%	50.1	45.4	44.2	40.8
0.3%	51.6	47.5	46.8	41.5
0.4%	49.8	45.1	44.0	39.2

Table 5. Splitting Tensile Strength of Recycled Concrete under Different Mix Proportions at 28 Days (MPa)

BF	RCA=0%	RCA=40%	RCA=50%	RCA=60%
0%	3.85	3.25	3.12	2.85
0.2%	4.25	3.68	3.55	3.15
0.3%	4.65	4.12	3.98	3.45
0.4%	4.45	3.85	3.72	3.20

2. Chloride Penetration Resistance (Electric Flux)

The 6-hour electric flux results (shown in Table 6 and Figure 1) demonstrated a non-linear interaction between BF and RCA. For the 50% RCA group, the electric flux followed a distinct V-shaped trend with increasing BF content. The unreinforced RCA specimen exhibited a high flux of 3600 C. When 0.2% BF was introduced, the flux plummeted to the global minimum of 3150 C, which was even lower than the natural aggregate control group (3300 C).

The V-shaped trend can be explained by two competing mechanisms. On the descending branch (0–0.2% BF), the uniformly dispersed fibers formed a three-dimensional micro-reinforcement network within the cement matrix. This network physically severed the continuous capillary pathways that serve as primary transport channels for chloride ions. Simultaneously, the fibers bridged micro-cracks at the ITZ between old and new mortar, restricting crack widths and reducing interconnected porosity. In the high-altitude environment of Kunming, where accelerated early-age drying intensifies shrinkage cracking (Cao et al., 2019), this crack-bridging effect was particularly critical. On the ascending branch (0.2–0.4% BF), excessive fiber content caused agglomeration due to the high surface area and hydrophilic nature of basalt fibers. The fiber clusters entrapped mixing water and air, creating localized zones of elevated porosity and new interconnected channels that facilitated chloride migration. This resulted in the electric flux rebounding to 4100 C at 0.4% BF. Similar fiber agglomeration thresholds have been reported by Dong et al. (2020) and Xie et al. (2021) for BF-reinforced concrete systems. Consequently, 0.2% BF combined with 50% RCA was identified as the optimal mix for durability, as it achieved the balance point between the beneficial crack-bridging effect and the detrimental agglomeration effect (Ding et al., 2020).

Table 6. 6-Hour Electric Flux Test Results of Recycled Concrete under Different Mix Proportions (C)

Number	RCA	BF	6h Electric Flux
NAC	0%	0%	3300
B0 R50	50%	0%	3600
B0.2 R50	50%	0.2%	3150
B0.4 R50	50%	0.4%	4100

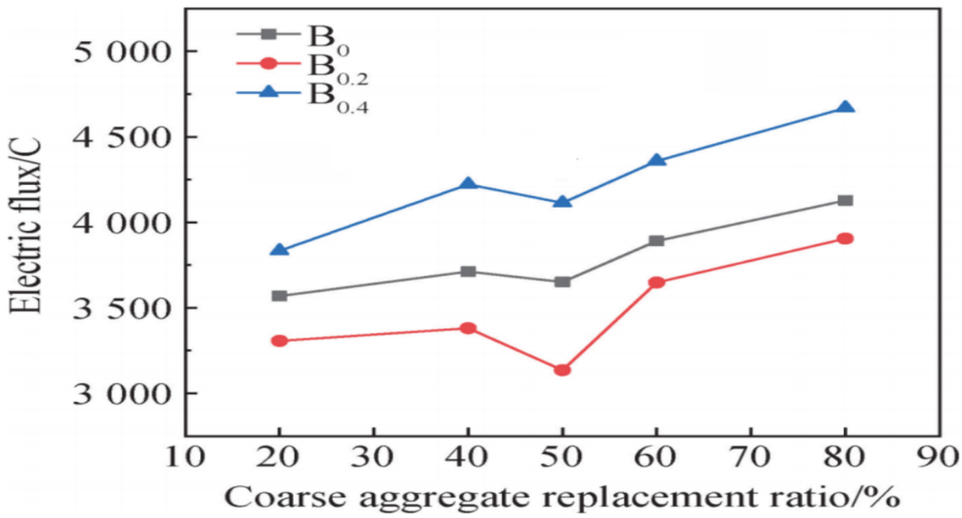

Figure 1. The 6-hour electric flux of recycled concrete with different BF dosages

3. Microstructural Analysis (MIP)

To elucidate the macroscopic durability enhancement observed in Sections 1 and 2, MIP tests were conducted to characterize the internal pore structure. The 0.2% BF optimally refined the pore structure, reducing the total porosity to the lowest value of 8.528%. More importantly, it altered the pore size distribution: the proportion of harmless and less-harmful pores (<100 nm) peaked at 68.52%, an increase of 3.4% over the unreinforced RCA group. The fibers physically dissected large, harmful capillary pores (>100 nm) into closed, harmless micro-pores. This microstructural refinement directly corresponds to the macroscopic performance trends presented earlier. Specifically, the 13.0% reduction in water absorption at 0.2% BF (Table 3) is consistent with the reduced total porosity and the conversion of interconnected capillary pores into isolated micro-pores. Furthermore, the superior electric flux performance of the B0.2 R50 group (3150 C, Table 6)—which outperformed even the natural aggregate control—can be quantitatively attributed to the severing of capillary transport pathways, as the increase in harmless pores (<100 nm) to 68.52% effectively eliminated the continuous channels required for chloride ion migration. These findings are consistent with Chen et al. (2021), who demonstrated that attached mortar content in RCA governs capillary porosity, and with Shi and Yuan (2018), who established that pore sizes below 100 nm do not contribute significantly to permeability-driven transport in cementitious materials. The MIP results therefore provide a mechanistic explanation for both the V-shaped durability trend and the identification of 0.2% BF as the optimal dosage for chloride resistance.

Conclusions

Based on the experimental investigation of BF-reinforced recycled concrete under high-altitude conditions in Kunming, the following conclusions were drawn:

1. V-shaped Control of Water Absorption: BF effectively mitigated the moisture loss associated with RCA in high-altitude environments. The 0.2% dosage was optimal, reducing water absorption by 13.0% through the restriction of interconnected voids.

2. Mechanical Enhancement and Toughening: A BF dosage of 0.3% provided the highest mechanical benefit, notably increasing the splitting tensile strength by 27.6%. The fibers bridged the ITZ, compensating for the inherent brittleness of RCA and providing a ductile failure mode.

3. Optimal Durability Configuration: The combination of 0.2% BF and 50% RCA was established as the optimal mix for chloride penetration resistance. It achieved the lowest electric flux of 3150 C, outperforming conventional concrete by severing physical capillary pathways.

4. Microstructural Mechanism: MIP analysis confirmed that 0.2% BF minimized total porosity (8.528%) and significantly refined the pore structure. It converted harmful macro-pores into harmless micro-pores (<100 nm), which accounted for 68.52% of the total volume, fundamentally blocking chloride ingress.

Future Work

1. Long-Term Durability Assessment: Future research should evaluate the long-term field performance of BF-RCA concrete under complex high-altitude conditions, such as freeze-thaw cycles, dry-wet alternations, and severe UV exposure.

2. Nanoscale Characterization of ITZ: While MIP provided overall pore metrics, future studies could employ Scanning Electron Microscopy (SEM) and Energy Dispersive

Spectroscopy (EDS) to quantify the chemical bonding mechanisms at the fiber-mortar interface.

3. Life-Cycle Assessment (LCA): A comprehensive cost-benefit and environmental impact analysis should be conducted to support the large-scale industrial promotion of BF-recycled concrete in southwestern China.

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