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

Jinlan He[1], Chaiporn Supahitanukool[1], Ritthichai Ratchapan[1] and Winai Ouypornprasert[2]*

Faculty of Engineering and Technology, Pathumtani University[1]

Faculty of Engineering and Technology, Pathumtani University[1]*

College of Engineering, Rangsit University[2]

Corresponding author's e-mail: ritthichai.r@ptu.ac.th

Abstract

Recycled coarse aggregate (RCA) supports sustainable construction but suffers from high porosity and poor chloride resistance, worsened by the low air pressure and dry climate of high-altitude areas like Kunming, China. Although basalt fiber (BF) improves concrete performance, its micro-macro effects on RCA concrete under such conditions remain unquantified. This study investigated flexural, compressive, and chloride penetration properties of concrete with RCA replacement at 0–60% and BF at 0–0.4%, testing water absorption, mechanical strength, and 6-hour electric flux, supplemented by MIP microstructural analysis. Water absorption and electric flux showed a "V-shaped" trend with increasing BF. Optimal mechanical performance occurred at 0.3% BF (27.6% increase in splitting tensile strength), while the best durability balance was 0.2% BF with 50% RCA, reducing electric flux to 3135.5 C—outperforming the natural aggregate control. MIP confirmed that 0.2% BF refined the pore structure, raising harmless pores (<100 nm) to 68.52% and severing capillary chloride pathways. These findings offer practical guidance for climate-adaptive recycled concrete mix design in high-altitude regions.

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

Introduction

Rapid urbanization has generated massive construction waste, making RCA use in concrete essential for carbon neutrality goals (Xiao, 2021). However, RCA's micro-cracks and residual mortar cause higher water absorption and inferior chloride resistance, compromising durability (Chen et al., 2021; Yan, 2013). In high-altitude areas like Kunming (1891 m), low atmospheric pressure and dry climate accelerate moisture loss and shrinkage cracking (Cao et al., 2019). Basalt fiber (BF), an eco-friendly material with high tensile strength and concrete-compatible thermal expansion (Wu, 2020), can bridge micro-cracks and enhance RCA concrete strength (Dong et al., 2020; Li et al., 2017). Yet most studies were conducted under normal conditions, leaving the synergistic effect of BF and RCA on chloride resistance under high-altitude constraints uninvestigated (Liu et al., 2021; Xie et al., 2021). This study therefore aimed to: (1) evaluate BF dosage and RCA replacement effects on physical and mechanical properties; (2) quantify chloride penetration resistance via electric flux; and (3) elucidate pore-refinement mechanisms using MIP (Shi & Yuan, 2018; Ding et al., 2020).

Materials and Methods

1. **General** This study used a laboratory comparative experimental approach with one control group and multiple BF-reinforced groups. Mechanical tests followed GB/T 50081-2019 and chloride penetration resistance was evaluated per GB/T 50082-2009, ensuring reliability and cross-study comparability.
2. **Materials** P·O 42.5 Portland cement was used with continuous graded natural coarse aggregate (5–20 mm) and Class II RCA from Kunming demolition waste (water absorption 12%, crushing index 20%). Natural medium sand (fineness modulus 2.3) served as fine aggregate. Basalt fiber (Sichuan Aerospace Tuoxin; 18 mm length, 17.4 μm diameter, 2500 MPa tensile strength) was incorporated. A polycarboxylate superplasticizer adjusted workability, and an air-entraining agent compensated for bubble loss due to high-altitude low pressure.

3. **Mix Proportion Design** A C30 target strength (w/b ratio 0.48) was designed with four BF fractions (0%, 0.2%, 0.3%, 0.4%) and four RCA replacement ratios (0%, 40%, 50%, 60%), plus a natural aggregate control group. A two-stage mixing method was used: BF and fine aggregates were dry-mixed for 30 s, then coarse aggregates, cement, and water were added for 280 s. Specimens were cured at 20±2 °C and RH≥95% for 28 days. Detailed proportions are in Table 1.

Table 1. 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

4. Experimental Program

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 2. 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 2. 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%

BF significantly compensated for RCA-induced strength loss (Tables 3–4), with optimal enhancement at 0.3% BF. In the 50% RCA group, splitting tensile strength increased from 3.12 to 3.98 MPa (27.6% gain). The high-modulus fibers bridged the ITZ between old and new mortar, shifting failure from brittle rupture to a ductile "cracked but not broken" mode (Li et al., 2017; Liu et al., 2021).

Table 3. 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 4. 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 (Figure 1) showed a non-linear, V-shaped interaction between BF and RCA. For the 50% RCA group, the unreinforced specimen had a high flux of 3600 C, which dropped to a minimum of 3150 C at 0.2% BF—lower than the natural aggregate control (3300 C). At 0.2% BF, a uniform 3D fiber network severed capillary pathways and inhibited micro-crack propagation under high-altitude drying shrinkage. However, exceeding 0.2% BF (e.g., 0.4%) caused agglomeration defects that created new interconnected channels, rebounding flux to 4100 C. Thus, 0.2% BF with 50% RCA was identified as the optimal durability mix (Ding et al., 2020; Xie et al., 2021).

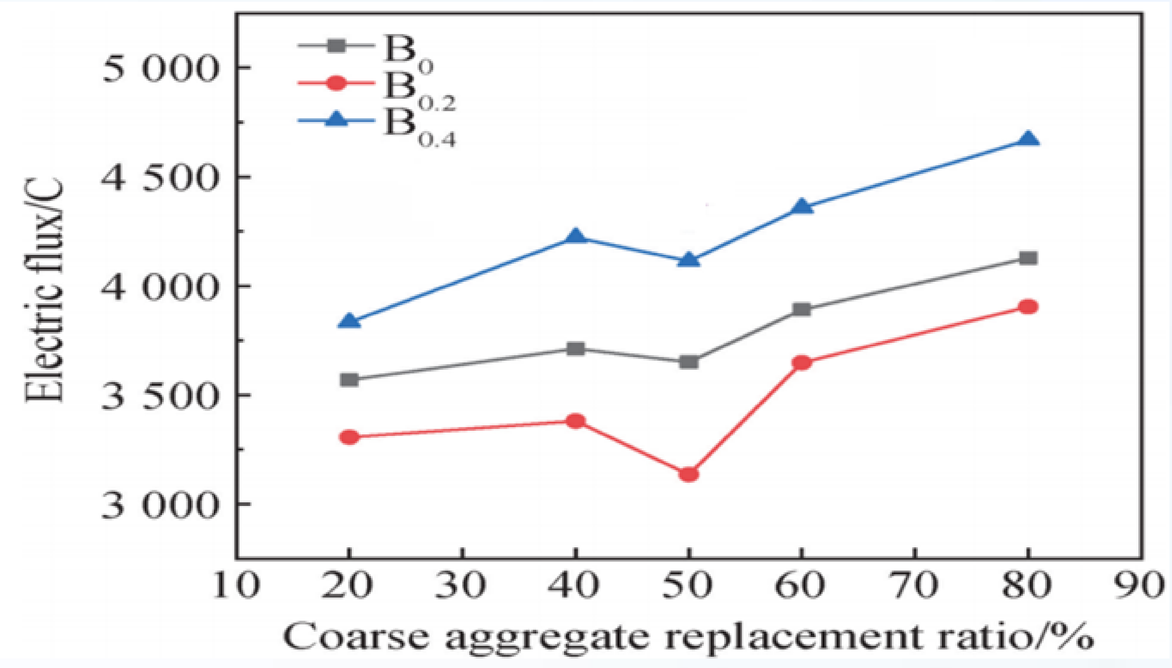

Figure 1. The 6-hour electric flux of recycled concrete with different BF dosages

3. Microstructural Analysis (MIP) MIP results showed that 0.2% BF optimally refined the pore structure, reducing total porosity to 8.528% and increasing harmless pores (<100 nm) to 68.52%—a 3.4% rise over the unreinforced RCA group. The fibers dissected large capillary pores (>100 nm) into closed micro-pores, blocking chloride migration paths and explaining the superior electric flux performance (Shi & Yuan, 2018; Chen et al., 2021).

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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