Effect of Pretreated Waste Cotton Fiber on Crack Control Performance of Concrete Pavement in Jintang, Sichuan

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Abstract

Concrete pavements in regions with high humidity and intense rainfall, such as Jintang, Sichuan, are highly susceptible to cracking and subsequent deterioration. Cracks, once formed, are widened by hydrodynamic forces and thermal stresses, significantly reducing pavement service life. Utilizing waste materials for crack control offers both economic and environmental benefits. This study investigates the potential of pretreated waste cotton fiber (WCF) to enhance the crack control performance of concrete pavements under simulated hot-humid and hydraulic scouring conditions. Waste cotton fibers were pretreated with a NaOH solution and incorporated into a C30 concrete mix at five different volume fractions (0.10%, 0.20%, 0.30%, 0.40%, and 0.50%), with a plain concrete mix (0.00%) serving as the control. The experimental program evaluated mechanical properties (compressive and flexural strength) and, crucially, the crack width development control capability under coupled environmental actions. Prism specimens were pre-cracked, subjected to thermal cycling (20°C–40°C), and then exposed to 72 hours of hydraulic scouring at 1 m/s. Crack width increment (Δw) and surface deterioration (mass loss, spalling area) were measured. The results indicate that the incorporation of pretreated WCF significantly improves the resistance to crack propagation under hydraulic action. Among the investigated mixtures, a fiber content of 0.20% by volume demonstrated the optimal balance between maintaining mechanical strength and providing superior crack control, exhibiting the lowest crack width increment and minimal surface deterioration. This study provides practical guidance for the design of durable, climate-adaptive concrete pavements and promotes the sustainable reuse of textile waste in infrastructure.

Keywords: Waste cotton fiber; concrete pavement; crack control; hydraulic scouring; thermal cycling; sustainability

Introduction

Concrete pavements are a fundamental component of modern infrastructure, prized for their high load-bearing capacity and long service life. However, their durability is severely challenged by cracking, which remains a predominant cause of premature failure (Lai, J., et al., 2020). Cracks create preferential pathways for water and aggressive agents to penetrate the concrete matrix, leading to reinforcement corrosion and material degradation. This issue is particularly acute in regions like Jintang County, Sichuan Province, which is characterized by a subtropical monsoon climate with frequent summer downpours and a high risk of flooding (China Meteorological Administration, 2020). In such environments, pavements are subjected to a damaging combination of thermal stress and intense hydraulic forces.

Temperature fluctuations generate tensile stress within the concrete. Cracking occurs when this tensile strain exceeds the material's limited capacity (Qu, Z.W., et al., 2024). Once a crack forms, its presence dramatically increases the permeability of the pavement. Research has shown that permeability can increase by two orders of magnitude as crack width grows from 0.05 mm to 0.3 mm (Lai, J., et al., 2020). During heavy rainfall, hydrodynamic pressure within these cracks further accelerates their propagation and causes surface deterioration (Reinhardt, H.W., & Jooss, M., 2003). Therefore, in flood-prone areas, effective crack control—specifically the ability to limit crack width development after initiation—is crucial for ensuring long-term pavement durability.

Fiber reinforcement is a well-established technique to improve the post-cracking properties of cementitious materials (Yoo, D., & Banthia, N., 2016; Bentur, A., & Mindess, S., 2007). Fibers bridge cracks and transfer tensile stress across them, effectively controlling their width under load (Banthia, N., & Gupta, R., 2004; Naaman, A.E., 2003). In recent years, the use of waste and natural fibers has gained attention for its potential to enhance sustainability in construction. Jintang County generates a significant amount of waste cotton fiber annually. Studies have shown that such fibers can improve the tensile strength and ductility of concrete and reduce brittle fracture (Correia, J. R., 2022). However, the incorporation of fibers can also affect the compressive and flexural strength of concrete, both critical for structural safety. Furthermore, the specific performance of waste cotton fiber in controlling crack width under the combined effects of thermal cycling and hydraulic scouring, which are typical of Jintang's climate, requires systematic investigation.

Accordingly, this study aims to evaluate the performance of pretreated waste cotton fiber-reinforced concrete for pavement applications under simulated hot-humid and high-rainfall conditions. The research focuses on (1) analyzing the effects of pretreated fiber additions on the compressive and flexural strength of concrete; (2) evaluating the crack width development control capacity of fiber-reinforced concrete after crack initiation under hydraulic scouring; and (3) developing appropriate waste cotton fiber concentrations for concrete pavement under high-pressure flood conditions. By identifying the optimal fiber dosage that balances mechanical integrity with superior crack control, this study seeks to provide practical mix design guidance for durable and climate-adaptive concrete pavements, while also promoting the beneficial reuse of local waste materials.

To achieve these objectives, a controlled laboratory experimental program was designed, including material characterization, mix proportioning, specimen preparation, mechanical testing, and a novel durability assessment involving pre-cracking, thermal cycling, and hydraulic scouring, as described in the following Materials and Methods section.

Materials and Methods

1. General

This study employed a controlled laboratory experimental design to determine the optimal dosage of pretreated waste cotton fiber (WCF) for C30 concrete pavements under simulated climatic conditions representative of Jintang, Sichuan. The methodology included material characterization, mix design, specimen preparation, mechanical testing, and a coupled durability test involving thermal cycling and hydraulic scouring. All procedures complied with relevant national and international testing standards to ensure reliability and reproducibility.

2. Materials

In this study, the selection of constituent materials was carried out to ensure consistency with typical construction practices and to maintain experimental reliability. All materials were commercially available construction materials selected based on compliance with relevant standards and suitability for producing C30 concrete for pavement applications. As summarized in Table 1, five main materials were used, including cement, coarse aggregate, fine aggregate, waste cotton fiber, and mixing water, together with their corresponding specifications.

Table 1. Specifications of Materials Used in the Experimental Program

Material	Specification
Cement	Ordinary Portland Cement P·O 42.5
Coarse aggregate	Crushed stone 5–20 mm
Fine aggregate	Medium sand (FM ≈ 2.6)
Fiber	Waste Cotton Fiber (WCF), length 18 mm,Diameter: 18－25 μm, NaOH-pretreated
Water	Potable tap water

Note: Waste cotton fibers were pretreated by immersion in a 5% w/v NaOH solution for 24 hours, then rinsed and dried at 60°C.

(a) Cement (b) Coarse aggregate

(c) Fine aggregate (d) Water

(e) Waste Cotton Fiber (f) NaOH

Figure 1. Materials used in the experimental program

3. Concrete Mix Proportion

To accurately evaluate the effect of WCF dosage, the base concrete mix was kept constant for all specimens, with only the fiber content varied. As shown in Table 2, five fiber volume fractions (0.00–0.50%) were adopted while all other mix components remained unchanged for comparison. The maximum fiber content of 0.50% by volume was selected based on findings from previous studies (Chandar & Sangeeth Kumar, 2022; Pham, 2025), which reported that natural and waste fiber dosages exceeding 0.50% typically resulted in significant fiber agglomeration, severe workability reduction, and difficulties in achieving uniform fiber dispersion within the concrete matrix. Moreover, preliminary trial mixes in this study confirmed that fiber contents above 0.50% produced unacceptable slump values and visible fiber clumping, rendering the mix unsuitable for pavement construction. The selected range of 0.00% to 0.50% was therefore considered representative of practically applicable fiber dosages for pavement concrete applications.

Table 2. Concrete Mix Proportions for Different WCF Volume Fractions

Fiber Vol.%	Cement (kg/m³)	Water(kg/m³)	Sand(kg/m³)	Gravel(kg/m³)	WCF(kg/m³)
0.00%	380	190	684	1026	0
0.10%	380	190	684	1026	1.44
0.20%	380	190	684	1026	2.88
0.30%	380	190	684	1026	4.32
0.40%	380	190	684	1026	5.76
0.50%	380	190	684	1026	7.20

Note: Fiber dosage calculated by volume of concrete. Fiber density = 1440 kg/m³.
The water–cement ratio was fixed at 0.50.

4. Experimental Program

4.1. Specimen Preparation

Concrete specimens were prepared using a forced mixer. To ensure uniform fiber dispersion, fibers were introduced during the dry mixing of aggregates, and the mixing duration was extended to 180 seconds. Cubes (150 mm) were cast for compressive strength tests, while prisms (100 × 100 × 400 mm) were cast for flexural strength and crack development tests. Specimens were cured at 20 ± 2°C and RH ≥95% for 28 days before testing.

Table 3. Experimental Groups and Specimen Allocation

Group	Fiber Vol.%	Specimens per Test	Total Specimens
F0	0.00%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11
F1	0.10%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11
F2	0.20%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11
F3	0.30%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11
F4	0.40%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11
F5	0.50%	3 cubes + 3 flexural prisms + 5 pre-cracked prisms	11

Each fiber dosage group consisted of multiple cube and prism specimens to ensure statistical reliability and reduce experimental error.

(a)

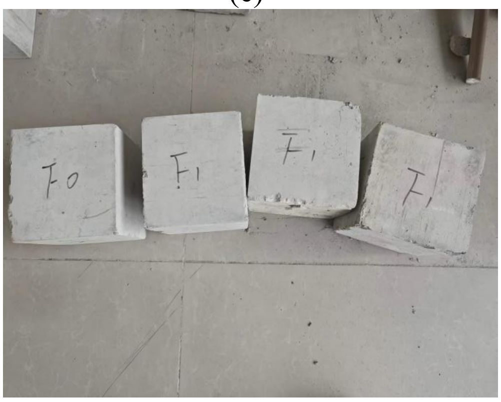
(b)

(c)

(d)

(e)

(f)



(g)

(h)

(i)

Figure 2 Specimen preparation process: (a) NaOH pretreatment of waste cotton fibers by immersion, (b) Environmental curing chamber, (c) Forced concrete mixer, (d) Casting concrete into prism molds, (e) Pouring fresh concrete mix, (f) Slump test measurement, (g) Labeled cube and prism specimens after demolding, (h) Prism specimens stored for curing, and (i) Close-up of a labeled prism specimen (F1)

4.2. Mechanical Property Test

Compressive strength and flexural tensile strength were measured according to GB/T 50081-2019 using a hydraulic compression testing machine and a universal testing machine. Flexural strength testing (third-point loading) followed ASTM C78/C78M-22. These tests represent the primary structural performance indicators of pavement concrete.

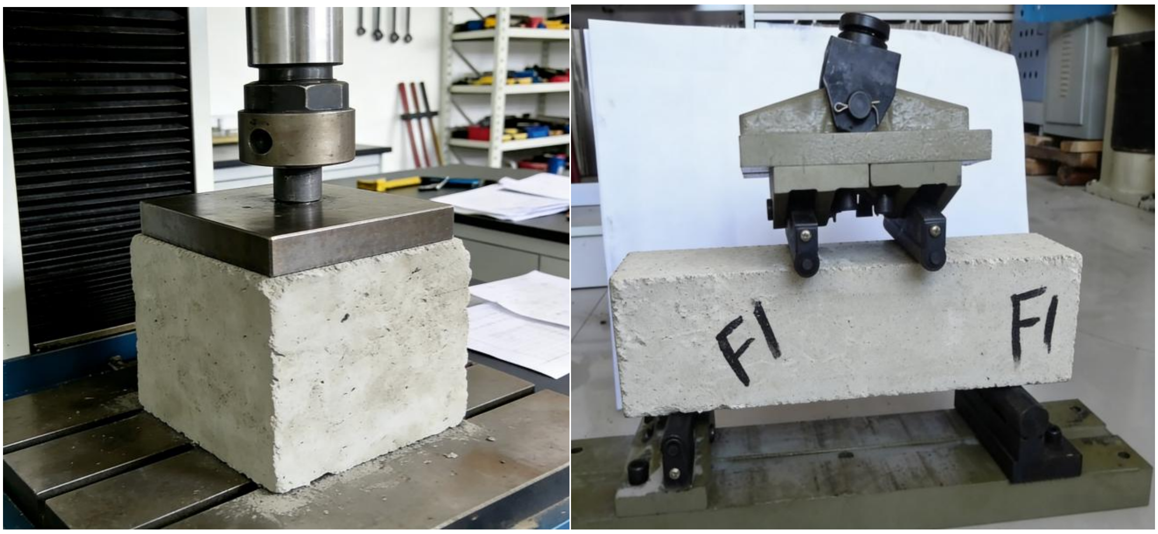


Figure 3 Flexural strength testing setup: (left) prism specimen positioned on the universal testing machine under third-point loading, and (right) close-up of the loading arrangement on the prism specimen.

4.3. Pre-Crack Preparation and Durability Simulation

To evaluate crack control performance under realistic environmental sequences, a multi-stage durability test was designed.

Pre-Crack Preparation: To simulate naturally occurring transverse cracks induced by thermal stress, flexural prisms were subjected to third-point loading until a visible crack (0.10–

0.20 mm) formed at the mid-span bottom surface. Loading was then immediately stopped, and the specimen was unloaded.

Figure 4 Pre-cracked prism specimen (F1) after controlled third-point loading, showing a visible transverse crack (0.10–0.20 mm) at the mid-span bottom surface.

Thermal Cycling Simulation: Pre-cracked specimens were subjected to 7 temperature cycles (24 h per cycle) in an environmental chamber to simulate summer diurnal temperature fluctuations. Each cycle consisted of 40°C for 8 h (daytime) and 20°C for 16 h (nighttime). The test was performed under the general environmental conditions specified in GB/T 50082-2024.

Figure 5 Pre-cracked prism specimens placed inside the environmental chamber for thermal cycling simulation (7 cycles, 40°C/20°C).

Hydraulic scouring test: After thermal cycling, test the specimens in a hydraulic scouring device to simulate rainfall runoff effects. The test is conducted in clean water at a temperature of 20 ± 2°C, with a flow rate of 1 m/s, and a total duration of 72 hours.

Figure 6 Hydraulic scouring test apparatus used to simulate rainfall runoff effects on pre-cracked specimens at a flow rate of 1 m/s for 72 hours.

4.4. Crack Width and Surface Deterioration Measurement

Crack width was measured at three marked points along the crack (at 1/4, 1/2, and 3/4 span) using a digital vernier caliper (accuracy ±0.01 mm) both before thermal cycling (w_0) and after hydraulic scouring (W_1), following the crack measurement method specified in GB/T 50152-2012 . The average crack width increment (ΔW) and the Crack Control Performance Index (CCPI) were calculated using Equations (1) and (2), respectively:

$$\Delta W = W_1 - W_0 \tag{1}$$

$$CCPI = \frac{W_1 - W_0}{W_0} \tag{2}$$

Where

W_1 is the average crack width after thermal cycling and hydraulic scouring (mm)

W_0 is the initial average crack width before thermal cycling (i.e., immediately after pre-cracking) (mm)

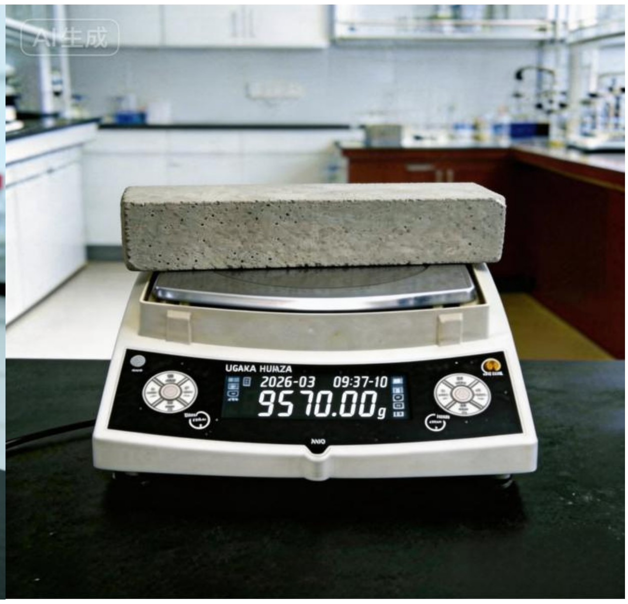
Surface deterioration was quantified by measuring the mass loss rate (Rm) and the surface spalling area ratio (Ra) after scouring, with reference to the test methods for freeze-thaw resistance in GB/T 50082-2024 and for surface defects in GB/T 50784-2013, as defined in Equations (3) and (4), respectively:

$$R_m = \frac{Mo - Mt}{Mo} \quad Ra = \frac{As}{Ao} \times 100\% \tag{3}$$

Where

Mo is the initial mass of the specimen before hydraulic scouring(g)
Mt is the mass of the specimen after hydraulic scouring (g)
As is the total surface spalling area measured after hydraulic scouring (mm^2)
Ao is the total original surface area of the specimen exposed to scouring (mm^2)

(a)



(b)

(c)

(d)

Figure 7 Crack width and surface deterioration measurement: (a) Crack width observation under a stereo microscope, (b) Mass measurement of specimen on a precision digital balance, (c) Crack width measurement using a digital vernier caliper (reading: 0.23 mm), and (d) Visual inspection and measurement of surface spalling area.

5. Data Analysis

Test results were evaluated using comparative statistical analysis. For each test, the mean value was calculated together with the standard deviation (SD) and coefficient of variation (CV) to ensure data reliability. Mechanical strengths were compared across fiber dosages. One-way analysis of variance (ANOVA) was conducted to evaluate the statistical significance of fiber dosage on crack width increment (Δw), mass loss rate (Rm), and surface spalling area ratio (Ra). The significance level was set at $\alpha = 0.05$.

Results

1. Workability Observation

The experimental slump test results indicated that increasing WCF dosage gradually reduced the workability of fresh concrete, attributed to fiber interlocking and increased internal friction. Mixes containing low fiber volume fractions (≤0.20%) maintained acceptable workability suitable for pavement construction. At 0.50% fiber content, the mix became notably stiff and difficult to handle.

2. Compressive Strength

The addition of pretreated WCF exhibited a dosage-dependent influence on compressive strength. A slight compressive strength increase of approximately 2–3% was observed at the 0.10% and 0.20% fiber content compared with the control mix. At dosages of 0.30% and above, compressive strength began to decrease, with the 0.50% mix showing a reduction of approximately 8–10%. This reduction is attributed to fiber agglomeration and the introduction of additional voids at higher fiber contents, which disrupts matrix continuity. These findings are consistent with those reported by Chandar and Sangeeth Kumar (2022), who observed that natural fiber additions at low to moderate dosages produced slight improvements in compressive strength, while higher dosages resulted in strength reductions due to increased porosity. Similarly, Pham (2025) reported that fiber agglomeration at excessive dosages disrupted the cement matrix and reduced compressive capacity, supporting the trends observed in this study.

3. Flexural Tensile Strength

Pretreated WCFs enhanced flexural tensile behavior due to their crack-bridging mechanism. The 0.10% and 0.20% fiber dosages increased flexural tensile strength by approximately 4–6% compared with the control mix. Fiber contents of 0.40% and 0.50% resulted in marginal improvement or a slight reduction due to fiber clustering and reduced matrix integrity. The observed flexural improvement is in agreement with Correia (2022), who reported that natural fiber reinforcement enhanced the flexural capacity of cementitious composites through effective crack-bridging and stress transfer mechanisms. Yoo and Banthia (2016) similarly demonstrated that fiber reinforcement improved post-cracking behavior and ductility, although the magnitude of improvement was highly dependent on fiber type, dosage, and dispersion quality.

4. Crack Width Development and Control

After the full sequence of pre-cracking, thermal cycling, and hydraulic scouring, all fiber-reinforced specimens demonstrated significantly improved crack control compared with plain concrete. As illustrated in Figure 8, the crack width increment (Δw) and Crack Control Performance Index (CCPI) varied considerably with fiber dosage. The plain concrete (0.00%) exhibited the highest Δw (approximately 0.095 mm) and CCPI (approximately 0.95), indicating severe crack propagation under the combined environmental actions.

Among all fiber-reinforced mixtures, the 0.20% fiber dosage demonstrated the best crack control performance, with the smallest crack width increment (Δw ≈ 0.025 mm) and the lowest CCPI (approximately 0.25). The CCPI for the 0.20% mix was reduced by approximately 50–55% compared to the control, with an average final crack width (w_1) controlled well below 0.25 mm. At higher fiber contents, crack control performance declined: the 0.40% and 0.50% dosages showed progressively increasing Δw and CCPI values, approaching levels comparable to the control mix. This deterioration is attributed to fiber agglomeration and weakened fiber-matrix bonding at excessive dosages. ANOVA results confirmed that fiber dosage had a statistically significant effect on Δw ($p < 0.05$). The significant improvement in crack control at moderate fiber dosages is consistent with the findings of Banthia and Gupta (2004), who demonstrated that fibers effectively bridged cracks and limited their propagation under sustained loading. Furthermore, Lai et al. (2020) reported that fiber reinforcement substantially reduced crack widths in pavement concrete, with optimal performance at moderate dosages, which aligns well with the present results. The performance decline at higher fiber contents also supports the observations of Naaman (2003), who noted that excessive fiber volumes could weaken the fiber–matrix interface and reduce overall crack control efficiency.

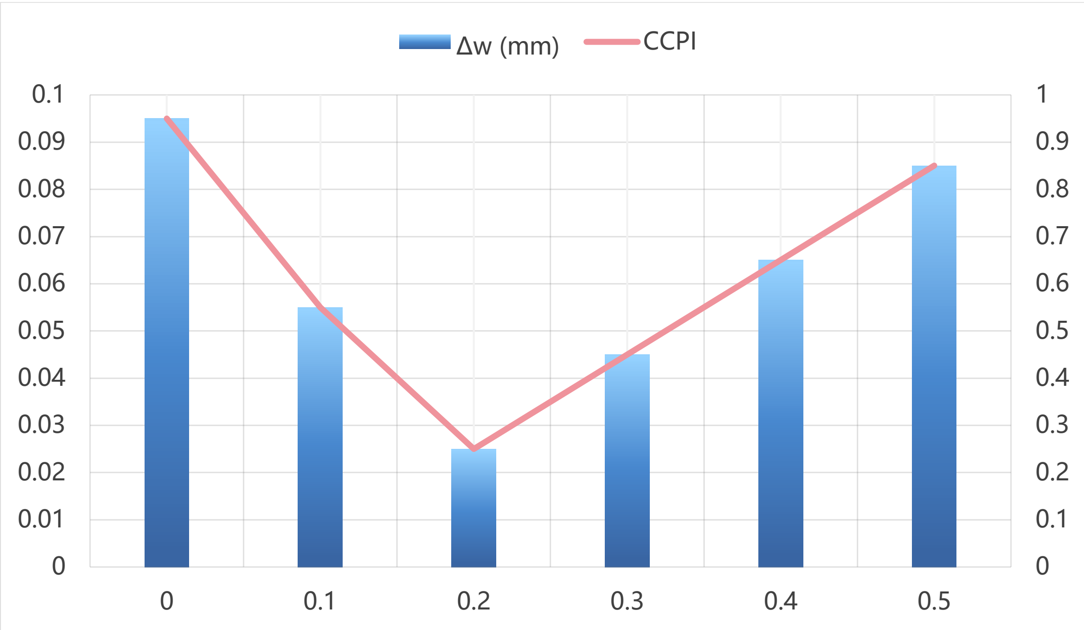


Figure 8 Effect of waste cotton fiber volume fraction on crack width increment (Δw) and Crack Control Performance Index (CCPI) after thermal cycling and hydraulic scouring.

5. Surface Deterioration after Hydraulic Scouring

The 0.20% fiber mixture exhibited the lowest surface deterioration, showing a mass loss reduction of approximately 60–65% and a spalling area reduction of 70–75% compared with the control mix. This indicates significantly improved resistance to hydraulic erosion. Higher fiber dosages (0.40% and 0.50%) showed increased deterioration compared to the 0.20% mix, likely due to a weaker fiber-matrix bond and surface defects caused by fiber agglomeration.

6. Overall Performance Evaluation

Considering mechanical strength, crack control (CCPI), and surface deterioration resistance together, the results indicate that 0.20% pretreated WCF by volume provides the most balanced performance. This dosage achieves minor improvements in strength while delivering the maximum benefit in controlling crack propagation and resisting hydraulic damage, as summarized in Table 4.

Table 4. Overall Performance Summary

Fiber Vol.%	Comp. Strength	Flex. Strength	Crack Control (CCPI)	Surface Deterioration	Overall Rank
0.00%	Baseline	Baseline	Poor	Poor	5
0.10%	Slight ↑	Slight ↑	Good	Good	2
0.20%	Slight ↑	Slight ↑	Excellent	Excellent	1
0.30%	↔	↔	Good	Good	3
0.40%	Slight ↓	Slight ↓	Moderate	Moderate	4
0.50%	↓	↓	Poor	Poor	6

Conclusions

This study is limited to laboratory-scale specimens and a controlled simulation regime. The experimental results demonstrate that the incorporation of pretreated waste cotton fibers significantly enhances the crack control performance of concrete pavements under simulated hot-humid and hydraulic scouring conditions. Among the investigated mixtures, a fiber dosage of 0.20% by volume (≈2.88 kg/m³) provided the most balanced improvement, effectively limiting crack width propagation and minimizing surface deterioration while maintaining acceptable mechanical strength and workability. Fiber contents exceeding 0.30% reduced workability and led to performance inefficiency due to fiber agglomeration. These findings provide practical guidance for climate-adaptive and sustainable mix design in durability-critical pavement applications.

Future Work

1. For practical pavement construction in high-rainfall regions like Jintang, a pretreated waste cotton fiber dosage of approximately 0.20% by volume (≈2.88 kg/m³) is recommended to achieve balanced improvements in crack control, durability, and mechanical performance while maintaining acceptable workability
2. Future research should investigate long-term field performance, the optimization of pretreatment methods (e.g., alternative chemicals or treatment durations), and the use of superplasticizers to further enhance fiber dispersion. Full-scale structural testing and a life-cycle assessment of the economic and environmental benefits would also confirm the practical applicability of waste cotton fiber-reinforced concrete in real engineering conditions.

These future investigations will support the practical and sustainable implementation of waste-derived fiber-reinforced concrete in real construction environments.

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