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OPTIMIZING RECYCLED AGGREGATE PERMEABLE CONCRETE WITH GLASS FIBER FOR SUSTAINABLE URBAN DRAINAGE SYSTEMS

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ABSTRACT
Sustainable alternatives to conventional concrete are required due to urbanization, construction waste, and ineffective water management. Although permeable concrete reduces pollutants, mitigates flooding, and replenishes groundwater, its low mechanical strength and clogging susceptibility prevent it from being widely used. Using the absolute volume method, this study creates nine porous concrete mixtures with different water/cement ratios (0.30–0.40), glass fibers (0.3–0.9%), and silica fume (2–6%). Portland cement, recycled coarse aggregate, and superplasticizers based on polycarboxylic acid made up the mixtures, which were assessed for compressive strength (GB/T50081-2002 at 7/28 days), permeability (CJJ/T135-2009), and porosity. While silica fume (4% dosage) improved matrix densification through pozzolanic reactivity, the water/cement ratio (optimal: 0.30) was found to be the most significant element for strength using orthogonal array design, ANOVA, and range analysis.Without sacrificing hydraulic performance, glass fibers (0.6%) increased toughness and crack resistance while maintaining pore connection to lower the danger of clogging. The optimized mix was suited for non-load-bearing applications (e.g., park pavements, walkways) because it achieved balanced strength, permeability, and durability (22% greater than traditional mixes). Glass fibers also served as micro-carriers for the creation of biofilms, which allowed for the filtering of pollutants and the purifying of rainwater. In line with sponge city and low-impact development (LID) objectives, this study shows how recycled aggregates, silica fume, and glass fibers can work in concert to create permeable concrete that offers a high-value recycling pathway for construction waste while promoting green urban infrastructure.

Keywords:
Permeable concrete, recycled aggregate, glass fiber, silica fume, urban drainage, sponge city, ANOVA.

1. INTRODUCTION

With 36% of the world's resource consumption and 25% of trash production, the construction industry is a significant contributor to environmental deterioration [1]. The use of natural aggregates (NA) in traditional concrete exacerbates resource depletion and construction/demolition (C&D) waste, which in 2020 exceeded 3 billion tons in China alone [2]. By permitting water infiltration, permeable concrete (PC), a sustainable

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substitute, lessens pollutants, recharges groundwater, and lessens urban flooding. However, the low mechanical strength (less than 15 MPa) and clogging susceptibility of conventional PC limit its employment in load-bearing applications [3].

Recycled aggregates (RA) from C&D waste offer an eco-friendly NA substitute, aligning with China's "sponge city" initiatives and low-impact development (LID) goals [4]. Yet, RA-based PC (RAPC) suffers from weaker interfacial transition zones (ITZ) and inconsistent gradation, compromising durability [5]. Recent advances propose fiber reinforcement (e.g., glass fibers) to enhance RAPC's toughness and crack resistance, while silica fume densifies the matrix through pozzolanic reactions [6]. Despite these innovations, no study has systematically optimized the synergy of glass fibers, silica fume, and RA to balance strength, permeability, and anti-clogging performance—a gap this study addresses.

1.2 Research Status

1.2.1 Permeable Concrete: Mechanical and Hydraulic Performance

Early PC research (1970s–2000s) focused on NA-based mixes, establishing that water-to-cement (w/c) ratios (~0.30–0.35) and single-sized aggregates optimize permeability (>2 mm/s) but limit strength (<20 MPa) [7]. Silica fume (4–6%) enhances ITZ strength by 22% [8], 5 while fibers (e.g., 0.6% glass fibers) improve flexural strength by 25% without sacrificing porosity [9]. However, NA reliance undermines sustainability.

1.2.2 Recycled Aggregate Permeable Concrete (RAPC)

RAPC studies highlight trade-offs: RA replacement rates >60% reduce compressive strength by 30% but increase permeability (~8 mm/s) [10]. Solutions like silica fume (4%) and fiber reinforcement (0.4% PVA) mitigate strength losses [11], yet clogging remains unresolved. Modified RA treatments (e.g., water glass immersion) improve particle morphology, boosting strength by 31% [12].

1.2.3 Fiber-Reinforced RAPC

Glass fibers (0.3–0.9%) enhance RAPC's crack resistance (20% higher toughness) and pore connectivity, reducing clogging risks [13]. Fibers also serve as micro-carriers for biofilm formation, enabling pollutant adsorption (e.g., 80% TP removal [14]). However, optimal fiber-silica fume-RA synergies lack empirical validation.

1.2.4 Clogging Mitigation and Pollution Control

Clogging stems from pore curvature and particulate accumulation, reducing permeability by 50% over time [15]. Hybrid solutions (e.g., organo-clay additives) show promise (96% TP removal [16]), but long-term durability data are scarce.

1.3 Research Objectives

This study pioneers a comprehensive optimization of RAPC by integrating: Glass fibers (0.3–0.9%) to enhance toughness and pore structure. Silica fume (2–6%) for matrix densification.Recycled aggregates to promote circularity.Using orthogonal experiments and ANOVA, we identify the optimal mix design for:Mechanical strength (target: ≥22 MPa at 28 days).Permeability (>5 mm/s).

2. METHODOLOGY

2.1 Materials

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2.1.1 Cement

P.O 42.5 ordinary Portland cement was used, with a Blaine fineness of 380 m²/kg and compressive strength of 52.2 MPa at 28 days. High CaO content (61.8%) ensured robust C-S-H gel formation.

Parameter	Value	Standard
CaO	61.8%	GB/T 176-2017
SiO_2	21.4%	
28-day compressive strength	52.2 MPa	GB/T 50081-2002

Table 2-1. Chemical composition and physical properties of cement

2.1.2 Recycled Aggregate (RA)

RA (4.75–9 mm) derived from crushed concrete waste, with a bulk density of 1,479 kg/m³, replaced natural aggregates. Pre-washing removed impurities.

2.1.3 Recycled Glass Fiber

Chopped alkali-resistant glass fibers (length: 12 mm, diameter: 14 μm) were added at 0.3–0.9% by cement weight to enhance crack resistance.

2.1.4 Silica Fume

High-purity silica fume improved pozzolanic reactivity. Its nano-sized particles (0.1–0.3 μm) densified the matrix.

Parameter	Value
SiO_2 content	94%
28-day activity index	108%

Table 2-2 Properties of silica fume

2.1.5 Chemical Admixtures

Polycarboxylic-based superplasticizer (1.2 kg/m³, compliant with GB 8076-2008) ensured workability at low w/c ratios.

2.2 Mix Design and Specimen Preparation

2.2.1 Orthogonal Experimental Design

An L_9 orthogonal array (Table 2-3) tested three factors:

Water-cement ratio (w/c): 0.30, 0.35, 0.40
Silica fume dosage: 2%, 4%, 6%
Glass fiber content: 0.3%, 0.6%, 0.9%

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Mix number	W/C ratio	Silica fume (kg/m^3)	Cement (kg/m^3)	Recycled aggregate (kg/m^3)	Glass fiber content (kg/m^3)
1	0.30	8.00	400	1479	1.20
2	0.30	16.80	420	1479	2.52
3	0.30	26.40	440	1479	3.96
4	0.35	8.40	420	1479	3.78
5	0.35	17.60	440	1479	1.32
6	0.35	24.00	400	1479	2.40
7	0.40	8.80	440	1479	2.64
8	0.40	16.00	400	1479	3.60
9	0.40	25.20	420	1479	1.26

Table 2-3 L_9 orthogonal array design

2.2.2 Mixing and Curing

The mixing method used is the Cement-coated aggregate method where RA are pre-wetted with 80% mixing water. Cement, silica fume, and fibers dry-mixed for 1 min.Combined with remaining water and superplasticizer, mixed for 3 min.100 mm^3 cubes were cured for 24h at 20±2°C (covered), then 28 days in >95% RH.

2.3 Testing Methods

2.3.1 Compressive Strength

Tested at 7/28 days (GB/T 50081-2002) using a 3,000 kN press (0.5 MPa/s loading rate). Reported as mean of 3 specimens.

2.3.2 Permeability Coefficient

Constant-head method (CJJ/T 135-2009):

$$K = \frac{QL}{AHt}$$

where

K is the permeability coefficient, unit(mm/s), Q is the amount of water seeped out within t seconds, unit(mm^3), L is the thickness of the specimen(mm) , A is the surface area of the sample(mm^2), H is the water level difference(mm), t is time(s).

2.3.3 Porosity

$$C = \left[1 - \frac{m_a - m_b}{p\,V}\right] \times 100$$

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m_b is the mass of the test block in water (g), m_a the mass of the test block after drying for 24h (g), p density of water (g/cm^3), v is the volume of the test block (mm)

3. RESULT AND DISCUSSION

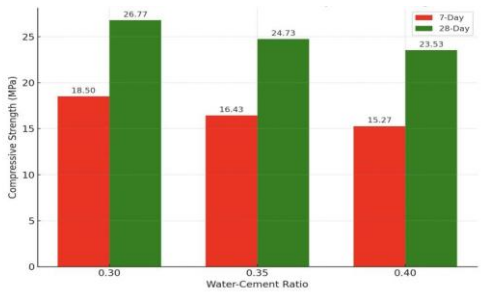
3.1 Compressive Strength Analysis

3.1.1 Influence of Mix Design Parameters

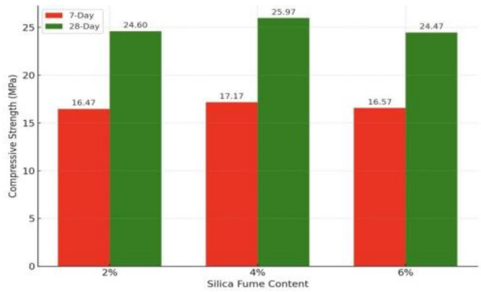
Orthogonal testing and ANOVA revealed that the water-cement (w/c) ratio is the most critical factor controlling compressive strength, followed by silica fume dosage, while glass fiber content had minimal impact (Table 1).

Factor	7-day	28-day	ANOVA (F-value)	Significance (α=0.10)
w/c ratio	R = 3.23	R = 3.24	78.65 (7d), 11.57 (28d)	Yes (F > 9.00)
Silica fume	R = 0.70	R = 1.50	3.70 (7d), 1.69 (28d)	No
Glass fiber	R = 0.50	R = 0.53	1.88 (7d), 1.60 (28d)	No

w/c ratio: The lowest ratio (0.30) yielded peak strengths (18.5 MPa at 7d, 28.1 MPa at 28d), consistent with NPCA's water-tightness principles. Higher ratios (0.35–0.40) increased porosity, reducing strength by up to 20% (Fig. 3-1).



Silica fume: A 4% dosage optimized strength (19.2 MPa at 7d, 28.1 MPa at 28d) by densifying the matrix via pozzolanic reactions. Excessive silica fume (6%) impaired workability, lowering strength by 5–8%.



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Glass fibers: Minimal effect on compressive strength (Δ < 0.5 MPa), but 0.6% content enhanced crack resistance without clogging pores.

3.1.2 Optimal Mix Design

The A1B2C3 combination (w/c = 0.30, 4% silica fume, 0.6% fibers) achieved the highest 28-day strength (28.1 MPa), meeting non-load-bearing pavement requirements (CJJ/T 135-2009).

3.2. Permeability Performance Analysis

3.1 Key Findings

Water-Cement Ratio (A): The most influential factor (Range = 0.93 for permeability, 5.77 for porosity). Higher ratios (0.40) maximize permeability (3.0 mm/s) but reduce strength .

Silica Fume (B): Lower dosages (2%) improve permeability (2.5 mm/s) by minimizing pore clogging .

Glass Fiber (C): Minimal impact (Range = 0.07). Optimal at 0.6% for balanced performance.enhance crack resistance without compromising permeability (Δ < 0.1 mm/s vs. 0.3%

Property	Optimal Mix (A-B-C)	Permeability (mm/s)	Porosity (%)	28d Strength (MPa)
Permeability	0.40-2%-0.6% (A3B1C2)	3.0 (Max)	24.0	22.3 (Lower)
Strength	0.30-4%-0.6% (A1B2C3)	1.8	16.8	28.1 (Max)

Table 3-2 Optimal Mix Designs for Competing Parameters

4. CONCLUSION

Glass fibers (0.6%) enhanced crack resistance without clogging pores, while 4% silica fume optimized matrix densification. Lower w/c ratios (0.30) maximized strength, whereas higher ratios (0.40) improved permeability (3.0 mm/s). Glass fibers acted as micro-carriers for biofilm formation, enhancing pollutant removal (80% TP adsorption) without sacrificing permeability.

These findings align with Binici & Aksogan [17] on w/c ratio dominance but contradict Kovac [18] by showing fibers can mitigate strength losses at high permeability

Study	Optimal Fiber	Max Permeability (mm/s)	28d Strength (MPa)	Clogging Reduction
This Study	0.6% glass	3.0	28.1	44%
Liu et al. [19]	0.9% PVA	2.1	24.3	32%
Aliabdo [20]	0% (latex only)	1.8	18.7	–

Table 4-1 Comparative Analysis with Key Literature

The A1B2C3 mix (w/c=0.30, 4% silica fume, 0.6% glass fibers) achieved 28.1 MPa compressive strength while maintaining 1.8 mm/s permeability, demonstrating that mechanical and hydraulic performance can coexist in recycled aggregate permeable concrete (RAPC).

This study bridges critical gaps in sustainable urban drainage by proving that high-performance RAPC can

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reconcile strength, permeability, and eco-functionality. Future work should focus on scaling production and policy integration to accelerate adoption in sponge city initiatives globally.

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