Experimental Investigation of the Mechanical Properties in Polyacrylonitrile Fiber-Reinforced Pervious Concrete

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Abstract. This study investigates the impact of polyacrylonitrile fibers on the mechanical properties of pervious concrete using the orthogonal test method to examine the effects of fiber length and content on flexural and splitting tensile strength. The experimental results indicate that fiber content has a slightly greater influence than fiber length. As fiber content increases, both flexural strength and splitting tensile strength generally improve, with enhancements exceeding 10% when the content is at least 1.5 kg/m^3 . Under conditions of 20% designed porosity and a water-binder ratio of 0.25, pervious concrete reinforced with 6 mm polyacrylonitrile fibers at 2.0 kg/m^3 achieves a maximum flexural strength of 6.5 MPa—representing a 44% increase compared to concrete without fibers. To ensure both flexural and splitting tensile strength enhancements, the fiber content should be maintained at a minimum of 1.5 kg/m^3 , with 6 mm fibers providing superior reinforcement compared to 12 mm fibers.

Keywords: Pervious Concrete, Polyacrylonitrile Fiber, Polypropylene Fiber, Flexural Strength, Splitting Tensile Strength, Orthogonal Design

1 Introduction

Pervious concrete, entitled also as permeable or porous concrete, is a type of concrete that has interconnected voids that allow water and also air to go across it. Pervious concrete has great potential for use in many practical applications as a part of urban facilities that can add value through water harvesting and mitigating severe damage from floods[1]. It is widely used in the construction of pavements, parking lots, and sidewalks, among other applications.Chen Xiaoguang identifies high-performance permeable concrete as a critical future development direction[2].The addition of fibers to porous concrete has been the subject of numerous studies in recent years, with researchers examining the effects of diversified types and amounts of fibers on the material' s properties. Fiber reinforcement can enhance the strength, durability, and ductility of porous concrete, making it more suitable for use in structural applications. Polymer fibers, in particular, have shown promise in improving the properties of pervious concrete. They can increase the material' s resistance to cracking, improve its flexural strength, and enhance its heat-absorbing property . Research by Elavarasan

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S. indicates that polypropylene fibers can increase the strength of pervious concrete[4]. Studies conducted by BAO Yubin's team indicate that the addition of either PVA fibers or PE fibers improves the compressive strength, flexural strength and ultimate deflection of pervious concrete, and the enhancement effect of PVA fibers is better than that of PE fibers[5]. The effects of single addition of plastic steel fiber and polypropylene fiber alone on the mechanical properties, permeability and frost resistance of pervious concrete were comparatively studied by Zhou Jingshan's research group[6].SHAO Huiguang and ZHANG Qizhi used polypropylene fiber and basalt fiber as admixtures to improve the mechanical properties of concrete[7]. The porosity and permeability coefficient were used to study the effect of basalt fiber length and content on the properties of pervious concrete by GUO Zhendong's research team.[8]. LONG Luanzhen's research showed that when porosity levels are maintained at 20% and 22%, pervious concrete reinforced with polyacrylonitrile fibers can achieve maximum compressive strength values of up to 53.1 MPa[9].Building upon existing research, this paper mechanistically analyzes how polyacrylonitrile fibers enhance the flexural and splitting tensile strengths of pervious concrete.

2 Raw Materials

2.1 Cement Properties

P·O42.5 from Hubei Huaxin Cement Plant: its physical and mechanical performance indicators are detailed in Table 1.

Table 1. Test results of physical and mechanical performance indicators for cement

Water requirement of normal consistency (%)	Retained percentage for 0.08mm square mesh sieve (%)	Density (g/cm^3)	Cement mortar strength (MPa)			
			Compressive strength		Flexural strength	
			3d	28d	3d	28d
28	0.95	3.11	28.9	51.2	6.6	8.7

2.2 Crushed Stone

The Guami stone, sourced from Wuhan, Hubei, with a particle size ranging from 2.5mm to 10mm, undergoes cleaning and drying before use. The physical property test results are detailed in Table 2, while the particle gradation analysis results are presented in Table 3.

Table 2. Test results of gravel physical performance indicators

Apparent density(kg/m^3)	Void percentage of close packing (%)	Bulk density(kg/m^3)	
		Loose bulk density	Tap bulk density
2680	42	1400	1560

Table 3. Sieve analysis results of crushed stone

Mesh size	9.50	4.75	2.36	<2.36	Total
Residue on sieve (g)	144.94	1502.91	330	19.85	1997.7
Retained percentage (%)	7.25	75.15	16.5	0.49	99.39

2.3 Fibers

Polyacrylonitrile fiber(PANF), supplied by Shanghai Chenqi Chemical Technology Co., Ltd., is offered in lengths of 6mm and 12mm. It features a density of 1.18 g/cm³, a diameter of 12.7 μm, a tensile strength of at least 500 MPa and an elastic modulus of no less than 7.2 GPa.

2.4 Admixtures and Additives

Water Reducer: The polycarboxylate water reducer for permeable concrete offered by Shanghai Chenqi Chemical Technology Co., Ltd. achieves a water reduction rate of ≥25%.
Hydroxypropyl methylcellulose, supplied by Shanghai Chenqi Chemical Technology Co., Ltd., with a viscosity of 150,000.

Polyacrylate Emulsion: Supplied by Beijing Mengtai Weiye Building Materials Co., Ltd.

Fly Ash: Grade I, 45μm square-hole sieve residue at 9.8%, water demand ratio at 89%, density of 2.25 g/cm³, and 28-day activity index of 78.1%.

3 Mix Ratios and Forming Processes of Permeable Concrete

3.1 Proportioning of Concrete Mix

According to the "Technical Specification for Permeable Cement Concrete Pavement" (CJJ/T135-2023), the mix design of permeable concrete is based on the volumetric method. The designated porosity is 20%, with a water-binder ratio of 0.25. A two-factor, two-level orthogonal experiment was conducted, as outlined in Tables 4 and 5. Additionally, control groups KZ1 and PL1 without fiber were included in the study.

Table 4. Orthogonal design for pervious concrete flexural strength testing

Factors / Levels	A PANF content(kg/m³)	B PANF length(mm)
1	1.5	6
2	2.0	12

Table 5. Orthogonal design for splitting tensile strength test of pervious concrete

Levels \ Factors	A PANF content(kg/m^3)	B PANF length(mm)
1	1.00	6
2	1.57	12

The mix proportions, flexural strength, and splitting strength of pervious concrete are presented in Tables 6 and 7.

Table 6. Mix proportion for flexural strength testing of pervious concrete

Speci-men	Aggre-gate (kg)	Ce-ment (kg)	Fly Ash (kg)	Water (kg)	Cellu-lose (g)	Emul-sion (g)	Water reducer (g)	PANF (g)	Flexural strength（MPa）
KZ1	21.41	5.586	0.56	1.4	27.93	167.58	55.86	0	4.5
KZ2	21.41	5.586	0.56	1.4	27.93	167.58	55.86	21(6 mm)	4.9
KZ3	21.41	5.586	0.56	1.4	27.93	167.58	55.86	21(12 mm)	5.1
KZ4	21.41	5.586	0.56	1.4	27.93	167.58	55.86	28(6 mm)	6.5
KZ5	21.41	5.586	0.56	1.4	27.93	167.58	55.86	28(12 mm)	5.4

Note: Values in parentheses indicate fiber lengths, similarly hereinafter.

Table 7. Permeable concrete splitting tensile strength test mix ratio

Speci-men	Aggre-gate (kg)	Ce-ment (kg)	Fly Ash (kg)	Water (kg)	Cellu-lose (g)	Emul-sion (g)	Water reducer (g)	PANF (g)	Splitting tensile strength（MPa）
PL1	10.703	2.513	0.28	0.7	13.97	83.79	27.93	0	2.8
PL2	10.703	2.513	0.28	0.7	13.97	83.79	27.93	7(6 mm)	2.8
PL3	10.703	2.513	0.28	0.7	13.97	83.79	27.93	7(12 mm)	3.0
PL4	10.703	2.513	0.28	0.7	13.97	83.79	27.93	11(6 mm)	3.2
PL5	10.703	2.513	0.28	0.7	13.97	83.79	27.93	11(12 mm)	3.1

3.2 The Molding Process

The aggregate surface coating method is employed for feeding and mixing. The specific process is as follows:

Step 1: Thoroughly combine the water reducer, cellulose, emulsion, and water using an electric whisk to create a uniform solution.

Step 2: Incorporate the aggregate into the mixer.

Step 3: Blend half of the mixed solution in a mixer for 1 minute.

Step 4: Add cement, silica fume, and polyacrylonitrile fiber to the mixer, then mix thoroughly for 2 minutes.

Step 5: Add the remaining mixed solution and stir continuously for 8 - 10 minutes .

The flexural test specimens are prisms measuring 100 mm×100 mm×400 mm, with three specimens per group. The splitting tensile test specimens are cubes measuring 100 mm×100 mm ×100 mm, with six specimens per group. All specimens are fabricated in accordance with the industry standard "Pervious Concrete" (JC/T2558-2020)[10]. Cured for 28 days using standard methods, their flexural strength is tested following established procedures. Additionally, three specimens from each group are randomly selected to evaluate splitting tensile strength using standard methodologies.

4 Analysis and Results of Tests

4.1 Experimental Results

The range analysis method was utilized to identify the optimal production conditions for the flexural strength and splitting tensile strength of pervious concrete. The detailed calculation results are presented in Table 8 and Table 9.

Table 8. Range analysis of flexural trength range for permeable concrete

Factors / Range analysis	A Fiber content	B Fiber length
K_{1j}	10.0	11.4
K_{2j}	11.9	10.5
$\overline{K_{1j}}$	5.00	5.70
$\overline{K_{2j}}$	5.95	5.25
R_j	1.90	0.90

Table 9. Range analysis of splitting tensile strength of pervious concrete

Factors / Range analysis	A Fiber content	B Fiber length
K_{1j}	5.80	6.00
K_{2j}	6.30	6.10
$\overline{K_{1j}}$	2.90	3.00
$\overline{K_{2j}}$	3.15	3.05
R_j	0.50	0.10

Based on Tables 8 and 9, it is evident that for flexural strength, R_1 exceeds R_2, with fiber content having a greater influence than fiber length. The optimal fiber content is A_2, while the optimal fiber length is B_1—indicating that the highest flexural strength is achieved when 6mm polyacrylonitrile fibers are added at a dosage of 2.0kg/m³. This observation corresponds to KZ4, which exhibits the highest flexural strength. For splitting tensile strength, R_1 also surpasses R_2, with fiber content exerting a slightly greater effect than fiber length. The optimal fiber content remains A_2, whereas the optimal fiber length shifts to B_2, signifying that the highest splitting tensile strength occurs when 12mm polyacrylonitrile fibers are added at a dosage of 1.57kg/m³. Nevertheless, in practice, PL4 achieves the highest splitting tensile strength, marginally outperforming PL5.

4.2 Influencing Factors Analysis

Influence of Fiber Content. Based on Tables 6 and 7, the outcomes depicted in Figures 1 and 2 can be derived, respectively.

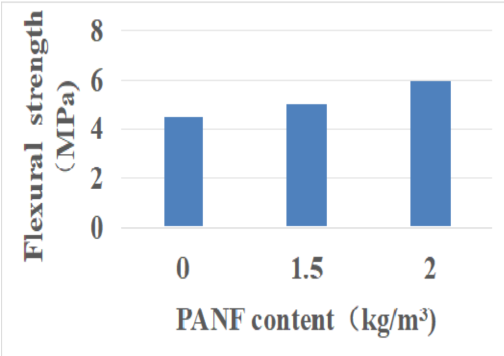

Fig. 1. Influence of PANF content on flexural strength

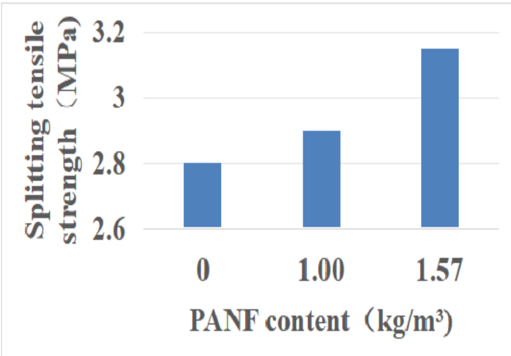

Fig. 2. Influence of PANF content on splitting tensile strength

As illustrated in Figure 1 and Table 6, the flexural strength of pervious concrete tends to increase with higher fiber content. When the fiber content rises from 1.5 kg/m³ to 2.0 kg/m³, the average improvement in flexural strength grows from 11% to 32%. In comparison to the non-fiber concrete specimen KZ1, KZ4 demonstrates a remarkable 44% enhancement in flexural strength, reaching 6.5 MPa—substantially surpassing the TZ3.5 flexural strength grade standard and showcasing a highly significant reinforcing effect. Similarly, Figure 2 and Table 7 indicate that the splitting tensile strength of pervious concrete improves as fiber content increases. With a rise in fiber content from 1.0 kg/m^3 to 1.57 kg/m^3, the average improvement in splitting tensile strength advances from 4% to 13%.

Fibers enhance the flexural strength and splitting tensile strength of pervious concrete due to their crack-resistant properties. Polyacrylonitrile fibers effectively disperse and absorb the energy concentrated at crack tips through mechanisms such as crack bridging, fiber debonding, and fiber pull-out. This energy is redirected to the separation process at the fiber/matrix interface and the frictional sliding of the fibers, thereby improving the overall strength of the concrete. As fiber content increases, the crack resistance effect is further amplified. Based on the results shown in Figures 1 and 2, when the fiber content exceeds 1.5 kg/m^3, the strength improvement can surpass 10%.

Impact of Fiber Length. Based on Tables 6 and 7, the outcomes depicted in Figures 3 and 4 can be derived similarly.

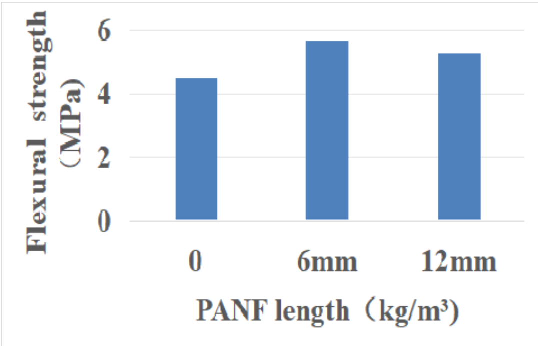

Fig. 3. Influence of PANF length on flexural strength

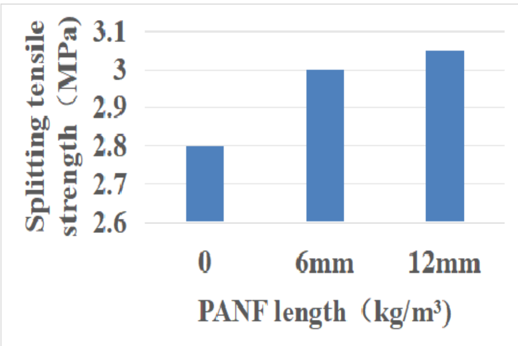

Fig. 4. Influence of PANF length on splitting tensile strength

According to Figures 3 and 4, regardless of fiber length, the flexural strength and splitting tensile strength of concrete are improved. For flexural strength, 6mm fibers demonstrate a slightly better enhancement effect than 12mm fibers. This is likely because, at the same dosage, the number of 6mm fibers is nearly double that of 12mm fibers, resulting in smaller average center-to-center spacing in the concrete. Fiber spacing theory suggests that the crack resistance of fibers is closely related to their distribution uniformity and density (spacing) in the matrix, with the critical factor being that fiber spacing must remain below a certain threshold to effectively inhibit microcrack propagation. Consequently, 6mm polyacrylonitrile fibers exhibit superior enhancement compared to 12mm fibers. For splitting tensile strength specimens, as the dosage does not exceed 1.6kg/m³, the fiber spacing remains relatively large, resulting in similar enhancement effects between 6mm and 12mm fibers.

5 Conclusion

(1) In both orthogonal tests, the impact of polyacrylonitrile fiber content exceeded that of fiber length.

(2) As the fiber content increases, the flexural strength and splitting tensile strength of pervious concrete improve accordingly.

(3) When 2.0 kg/m³ of 6 mm fibers was added, the flexural strength peaked at 6.5 MPa, reflecting an increase of over 40% compared to plain concrete. When the fiber content was limited to 1.0 kg or 1.57 kg, the higher value was selected, with 6 mm fibers achieving the highest splitting tensile strength—a 13% improvement over plain concrete.

(4) Polyacrylonitrile fibers with a 6mm length demonstrate superior reinforcement effects compared to those with a 12mm length.

(5) The fiber dosage should exceed 1.5 kg/m³ to achieve an increase of more than 10% in flexural strength and splitting tensile strength.

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