Research Article

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Research on the strength prediction for pervious concrete based on design porosity and water-to-cement ratio

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Abstract: The strength prediction of pervious concrete is hard to implement for the mix design due to the porous structure. This work studied the influence of the water-to-cement ratio on the fluidity, viscosity, and mechanical properties of cement paste. Then, the porosity, permeability, and compressive strength of the pervious concrete with various porosities were investigated, and the test results were fitted and analyzed. The result indicates that as the water-to-cement ratio increases, the viscosity of the cement paste reduces and the fluidity increases. The water-to-cement ratio has a negative linear relationship with net slurry strength. The porosity and permeability of pervious concrete fluctuate in accordance with the same rule as the water-to-cement ratio changes. The compressive strength of pervious concrete with varying design porosities increases initially, then declines as the water-to-cement ratio rises. According to the linear fitting analysis, when the water-to-cement ratio is constant, the permeability and compressive strength of pervious concrete have a positive and negative linear relationship with the design porosity, respectively. By analyzing the fitting results and combining the volume method of pervious concrete, a calculation method for mix proportion design is proposed to predict the strength of pervious concrete.

Keywords: strength prediction, pervious concrete, permeability, porosity, water-to-cement ratio

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1 Introduction

With the development of urbanization, the quality of our lives is continuously improving. At the same time, a series of environmental problems caused by urban construction are becoming more serious. Global warming, land degradation, and the heat island effect of which all these phenomena reveal the drawbacks of the development of industrial society [1–3]. In order to reduce environmental pollution and build an environment-friendly society, green materials would be widely used in city construction [4–6].

As a new environment-friendly pavement material with porous structure [7], pervious concrete may aid in reducing the environmental problems caused by urban flooding, lack of groundwater, and the blare of car horns because of its excellent water percolation, heat absorption, and noise reduction functions [8,9]. In order to balance urban development and ecological harmony, pervious concrete has been used in urban construction planning, such as low impact development technology [10], water-sensitive urban design [11], rainwater collection and storage technology [12], rainwater purification technology [13], and sponge city build [14]. However, compared with ordinary concrete, pervious concrete normally has lower strength and poorer durability [15]. In addition, when designing the mix ratio of pervious concrete, most design methods are based on porosity to control the permeability. However, predicting the strength of pervious concrete remains challenging, which limits its potential applications. As a result, many researchers have conducted investigations in order to identify more practical and efficient mix proportion design methods [16,17].

Studies have shown that the matrix properties affect the performance of concrete [18]. Tang *et al.* [19] studied the compressive strength of high-performance pervious concrete and found that the impact of each factor on the strength was in the following order: matrix properties > bone glue ratio > fine aggregate content. To improve the matrix properties, scholars have added modified materials to pervious concrete, such as fly ash [20], pumice powder [21], and silica fume [22]. Yuan [23] optimized the traditional "volume method" and proposed a mix ratio design method applicable to adding enhancers and modifiers. By measuring the specific surface area and fractal dimension of aggregates, the thickness of the paste coating of the aggregate can be effectively calculated [24]. The paste thickness of the coated coarse aggregate, the number of contact points, and the contact width between the coarse aggregates have been confirmed to significantly influence the strength, porosity, and permeability of pervious concrete [25]. Yang *et al.* [26] applied the coating method to the mix ratio design of recycled aggregate pervious concrete. By studying the coating thickness of recycled aggregate with different properties of cement slurry and mortar, a correlation model between the consistency of recycled fine aggregate sand, the fluidity of the cement slurry, and the mass ratio of medium sand/cement slurry was established, and a design method for the sand-containing pervious concrete mix ratio was proposed based on the paste thickness of recycled aggregates. Xie *et al.* [27] studied the effects of pervious concrete skeleton structure parameters on compressive strength and permeability performance. A mixed proportion design method based on skeleton structure was proposed to better predict the strength and permeability of pervious concrete. However, the mix ratio design method is too complicated to be effectively applied in practical engineering. The current mix ratio design methods of pervious concrete are mainly based on meeting the requirements of permeability performance, such as the specific surface area method and the volume method, which cannot guarantee the strength requirements [28].

In this study, the volume method was used to calculate the mix proportion of pervious concrete. The effect of the water-to-cement ratio on the viscosity, fluidity, and strength of cement slurry was investigated, and then, the impact of the design porosity and water-to-cement ratio on the compressive strength, porosity, and permeability of pervious concrete was studied. Combined with the volume method, a mixed proportion design method for predicting the compressive strength of pervious concrete was proposed by linear fitting analysis.

2 Experimental

2.1 Raw materials

A single graded aggregate with a diameter of 3–5 mm, as shown in Figure 1, was used for preparing samples. The aggregate properties are shown in Table 1. Ordinary Portland cement P O 42.5 manufactured by Conch Cement Corp. was utilized in this study. The cement has a density of 3.1 $g \cdot cm^{-3}$, and its physical and chemical properties meet the requirements of Chinese standard GB/T 175-2007 [29]. A polycarboxylate superplasticizer with a solid content of 52.14% was produced by the Jeede Chenchi Sponge City Construction Co., Ltd., and it was added in pervious concrete during the mixing process to improve its strength and workability. Tables 2 and 3 show the properties of cement and superplasticizer, respectively.

2.2 Mixture proportions and sample preparation

The water-to-cement ratio used in the test ranged from 0.26 to 0.41, and the step size was 0.03. The design porosity was 15, 20, and 25%, respectively. The dosage of reinforcer agents was 2.5% by mass of cement. Table 4 shows the mix ratios of pervious concrete.

The mixing procedure for the pervious concrete is depicted in Figure 2. Initially, all aggregates and 20% of the test water were mixed in a large mortar mixing pot. Once the aggregate surface was moistened, cement was added and mixed for 30 s to thoroughly encapsulate the

Figure 1: Aggregate.

Table 1: Performance index of coarse aggregate

Size (mm)	Silt content (%)	Apparent density (kg·m^{-3})	Close packing density (kg·m^{-3})	Stacked porosity (%)
3–5	0.78	2862	1691	40.9

Table 2: Chemical and physical properties of cement

Chemical composition (%)							Apparent density (g·cm^{-3})	Specific surface area (m^2·kg^{-1})
Cao	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O		
66.458	16.981	5.178	4.515	3.620	1.111	0.901	3.1	360

Table 3: Properties of superplasticizer

Parameters	Values
Chlorine content (%)	21.29
Na_2SO_4 content (%)	0.08
Solid matter (%)	52.14
Alkali content (%)	1.10
pH	3
Density (g·cm^{-3})	1.31

aggregate. Next, 50% of the test water was introduced and mixed for 60 s before being left to stand for 30 s. Finally, the superplasticizer was added and stirred for 120 s to produce fresh pervious concrete. The mold was filled with the freshly mixed pervious concrete in two layers, and the specimens were formed by tamping each layer 20 times with a 3 cm diameter steel rod. The size of the strength test specimens was 40 mm × 40 mm × 160 mm for cement slurry, while the dimensions of the permeability test specimens were ∅50 mm × 100 mm, and the compressive and porosity test specimens were 100 mm × 100 mm × 100 mm for the pervious concrete. The samples were covered with cling film for 24 h and then transferred to the standard curing room (the temperature is 20 ± 2°C, and the humidity is not less than 95%) until they reached the desired maturity.

Table 4: Mix proportions of pervious concrete

Group	W/C	Design porosity (%)	Components (kg·m^{-3})			
			Aggregate	Cement	Water	Enhancer
1	0.26	15	1657.2	464.9	120.8	11.6
2	0.29			442.1	128.2	11.1
3	0.32			421.5	134.8	10.5
4	0.35			402.7	140.9	10.1
5	0.38			385.5	146.4	9.6
6	0.41			369.7	151.5	9.2
7	0.26	20		379.1	98.5	9.4
8	0.29			360.5	104.5	9.0
9	0.32			343.7	109.9	8.6
10	0.35			328.3	114.9	8.2
11	0.38			314.3	119.4	7.8
12	0.41			301.4	123.5	7.5
13	0.26	25		293.2	76.2	7.3
14	0.29			278.9	80.8	6.9
15	0.32			265.8	85.0	6.6
16	0.35			253.9	88.8	6.3
17	0.38			243.1	92.3	6.1
18	0.41			233.2	95.6	5.8

2.3 Testing procedures

2.3.1 Fluidity and viscosity

In order to explore the influence of cement slurry properties on the performance of pervious concrete, the fluidity and viscosity of cement slurry were tested by removing the coarse aggregate from pervious concrete. The fluidity test was conducted in accordance with Chinese standard GB/T 8077-2000 [30]. The digital viscometer of type NDJ-8S was used to test the viscosity of the cement slurry.

2.3.2 Mechanical properties

The cement bending compression testing machine of type DYE-300B was used to measure the compressive strength and flexural strength of cement slurry in accordance with the Chinese standard GB/T 17671-1999 [31]. The compressive strength of the pervious concrete test was conducted by the hydraulic compression testing machine of type HG-YS600S according to the Chinese standard GB/T 50081-2019 [32]. All mechanical property tests of specimens were carried out after curing for 28 days.

2.3.3 Porosity

The porosity of the pervious concrete was measured according to American standard ASTM C1754 [33]. The caliper was used to measure and calculate the volumes of the three-dimensional dimension of pervious concrete specimens. Those specimens were dried in the oven at 105°C for 24 h, and then, their dry mass was weighed. The mass of pervious concrete in water was measured using a hydrostatic balance. The effective porosity of pervious concrete was computed according to the following equation:

$$v = \left[1 - \frac{m_1 - m_2}{\rho V}\right] \times 100\%, \tag{1}$$

where v is the porosity (%), m_1 is the dry mass of the sample (g), m_2 is the mass of the specimen in water (g), ρ is the density of water (g·cm^{-3}), and V is the volume of the specimen.

2.3.4 Permeability

Permeability tests were conducted by a constant head method according to the American standard ASTM-D2434-19 [34]. Then, the permeability coefficient of the pervious concrete was calculated by Eq. (2). The specimens were fastened using an imprison ring during the test to prevent water from flowing out of the side of the specimen. The permeability performance test equipment is shown in Figure 3.

$$K = \frac{QL}{AHt}, \tag{2}$$

where K is the permeability coefficient (mm·s^{-1}), Q is the water quantity collected within time t (mm^3), L is the specimen thickness (mm), A is the surface area of the specimen (mm^2), H is the head difference (mm), and t is the water collection time (s).

3 Results and discussions

3.1 Cement slurry performance

3.1.1 Fluidity and viscosity

The effect of the water-to-cement ratio on the rheological properties of cement slurry is shown in Figure 4. As the water-to-cement ratio rose, the fluidity first increased slightly (0.26–0.32) and then surged (0.32–0.41). Simultaneously, the viscosity first plunged (0.26–0.32) and then declined slowly (0.32–0.41), which is attributed to changes in the water film-layer thickness surrounding cement particles [35]. When the water-to-cement ratio was less than 0.32, the thinner water film layer between cement particles led to increased shear resistance between particles. Additionally, the cement particles adsorbed a large amount of water, resulting in a thickened the water film and reduced free water, so the effect of

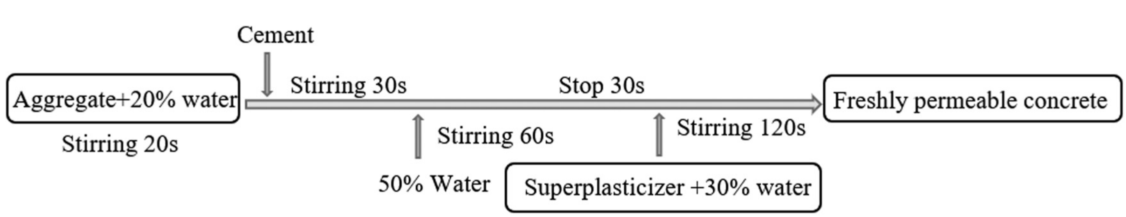

Figure 2: Pervious concrete mixing process.

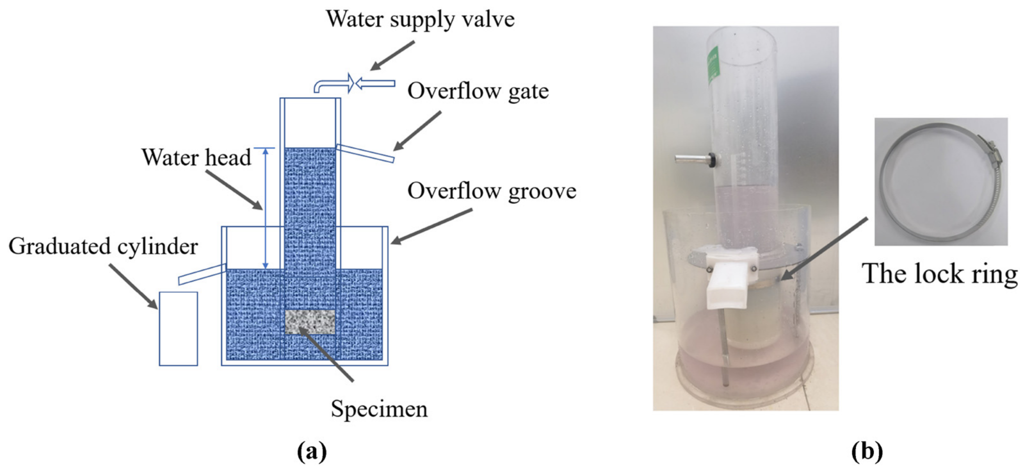

Figure 3: Equipment for permeability measurement of pervious concrete: (a) schematic diagram and (b) photograph.

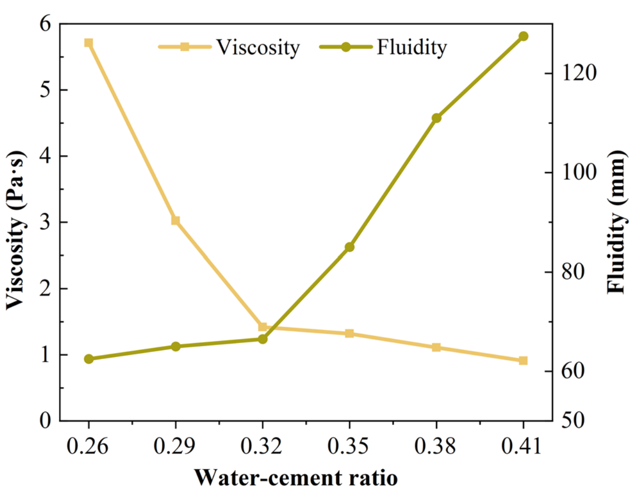

Figure 4: Influence of water-to-cement ratio on fluidity and viscosity of cement slurry.

the change of the water-to-cement ratio on the fluidity of the cementitious system was not apparent. When the water-to-cement ratio exceeded 0.32, the water film layer surrounding cement particles thickened and the interparticle resistance decreased, resulting in a weaker effect of the water-to-cement ratio on system viscosity. On the other hand, the excess water became free water, allowing the cement paste to flow more easily. Consequently, as the water-to-cement ratio increased further, the fluidity of the cement slurry increased significantly.

3.1.2 Mechanical properties

Figure 5 shows the effect of the water-to-cement ratio on the compressive strength and flexural strength of cement paste. The compressive strength and flexural strength of cement paste decreased as the water-to-cement ratio rose. This is because the cement hydration only requires a small amount of water. When the water-to-cement ratio increases, the hardened paste will generate more pores due to the evaporation of excess water, which reduces the compactness of the cement paste and affects its strength. The R^2 values of compressive strength and flexural strength were 0.972 and 0.993, respectively, indicating a significant linear relationship between the water-to-cement ratio and strength. The different slopes suggest that the water-to-cement ratio affects compressive strength and flexural strength to different degrees. Increasing the water-to-cement ratio from 0.26 to 0.41 resulted in a 31.36% decrease in compressive strength and a 21.9% decrease in flexural strength, demonstrating that the compressive strength is more susceptible to changes in the water-to-cement ratio.

3.2 Pervious concrete performance

3.2.1 Porosity

Figure 6 shows the effect of the water-to-cement ratio on the porosity of pervious concrete. When the design porosities were 15 and 20%, the measured porosity of the pervious concrete increased slightly as the water-to-cement ratio rose and then gradually decreased. When the volume method is used to calculate the mixed ratio of pervious concrete, a higher water-to-cement ratio results in a lower amount of cement. And the less cementitious material may not be able to completely fill the pores of pervious concrete, which will cause the porosity to rise. On the other hand, the cement slurry with a high water-to-cement ratio

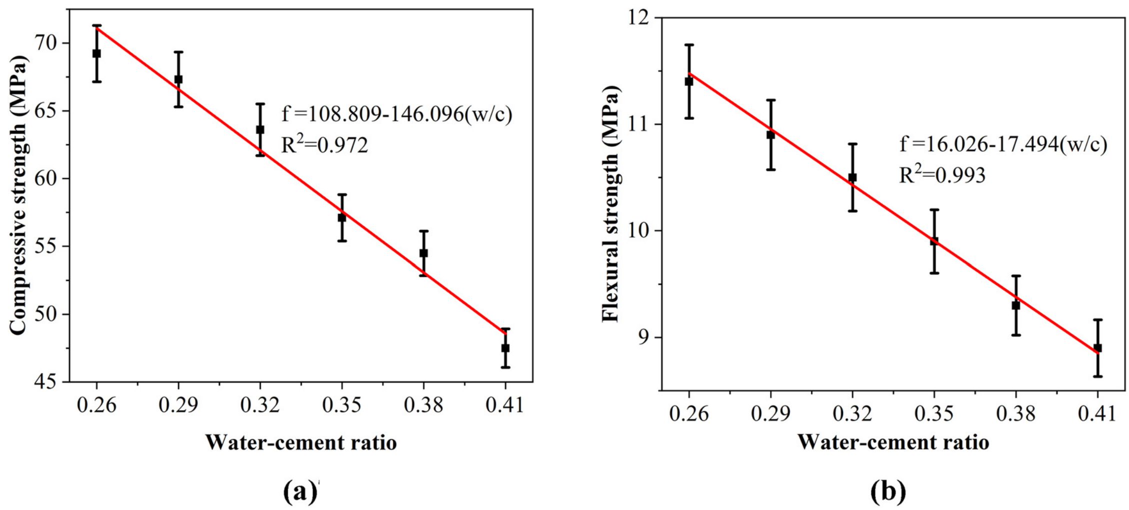

Figure 5: Effect of water-to-cement ratio on compressive strength and flexural strength of cement paste: (a) compressive strength and (b) flexural strength.

has better fluidity, and the cement slurry attached to the coarse aggregate will settle due to the increased fluidity. The settled cement slurry will block the pores at the bottom of the pervious concrete, decreasing the porosity. When the design porosity was 25%, the measured porosity of the pervious concrete decreased as the water-to-cement ratio increased. This is because the amount of cement significantly reduces in the raw material of pervious concrete at this time, the filling impact of paste on the pores of pervious concrete is weakened considerably, and cement slurry settlement primarily affects the change in porosity. Overall, the measured porosity values of pervious concrete are consistent with the design porosity, with a maximum error of less than 1.53%.

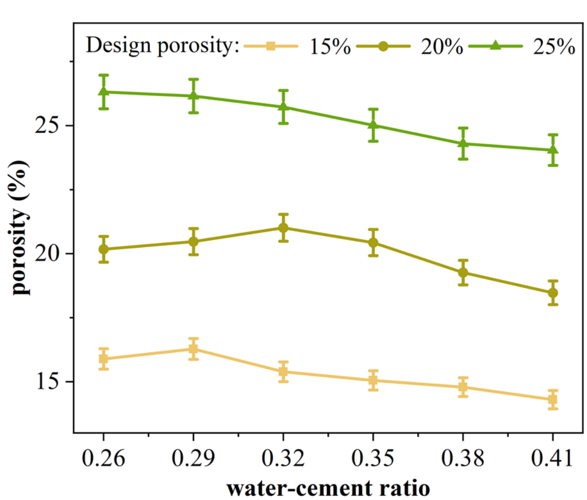

Figure 6: Effect of water-to-cement ratio on porosity of pervious concrete.

3.2.2 Permeability

Figure 7 shows the permeability coefficient of pervious concrete. The permeability of pervious concrete is mainly influenced by the characteristics of its pores, such as shape and quantity. The specimens have the same pore shape when the coarse aggregate size and shape are consistent. In this study, all samples were prepared using fine aggregates with a particle size of 3–5 mm, which means that the permeability depends on the number of pores. According to the effect of the water-to-cement ratio on the porosity of pervious concrete (Figure 6), the permeability coefficient and porosity of pervious concrete follow the same change rule.

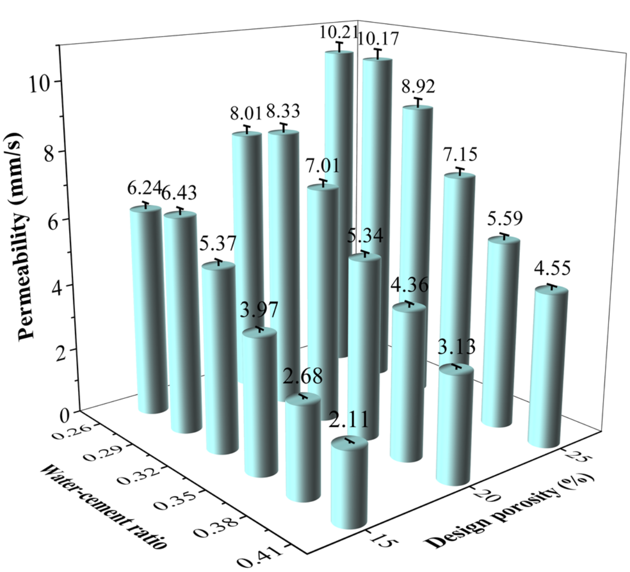

Figure 7: Permeability coefficient of pervious concrete.

This suggests that porosity affects the change in the permeability of pervious concrete. Furthermore, when the water-to-cement ratio changed from 0.26 to 0.41, the minimum values of permeability coefficients of pervious concrete with design porosity of 15, 20, and 25% decreased to 32.81, 37.58, and 44.74% of the maximum values, respectively. This indicates that the increase of porosity would weaken the effect of the water-to-cement ratio on the change of permeability of pervious concrete. The maximum permeability coefficient of the pervious concrete was 10.21 mm·s^{-1}, which was achieved when the water-to-cement ratio was 0.26 and the design porosity was 25%.

3.2.3 Compressive strength

Figure 8 shows the compressive strength of pervious concrete. When the design porosity was constant, the compressive strength of the pervious concrete first increased and then decreased as the water-to-cement ratio increased, reaching its maximum value at 0.35. This change differs from the variation rules of porosity and permeability of pervious concrete, as well as from the variation law of cement paste strength. When the water-to-cement ratio increased from 0.29 to 0.32, the maximum increase in compressive strength of pervious concrete with design porosity of 15, 20, and 25% was 5.1, 4.8, and 3.7 MPa, respectively. This phenomenon was in conjunction with the fluidity and viscosity of the cement slurry. When the water-to-cement ratio was less than 0.32, the slurry rheology was poor, making it difficult to effectively wrap the coarse aggregates, leading to unstable cohesiveness between aggregates and affecting the strength development of pervious concrete [36,37]. When the water-to-cement ratio was 0.32, the pervious concrete exhibited excellent workability and reached its best workability at 0.35. When the water-to-cement ratio was exceeded 0.35, the cement slurry wrapping the coarse aggregate had higher fluidity and was more susceptible to precipitation. In addition, the higher water-to-cement ratio led to lower cement paste strength. So the uneven distribution of cementitious materials and the low strength of the paste limited the strength development of pervious concrete [38]. When the water-to-cement ratio and design porosity were 0.35 and 15%, respectively, the maximum compressive strength of the pervious concrete was 32.5 MPa.

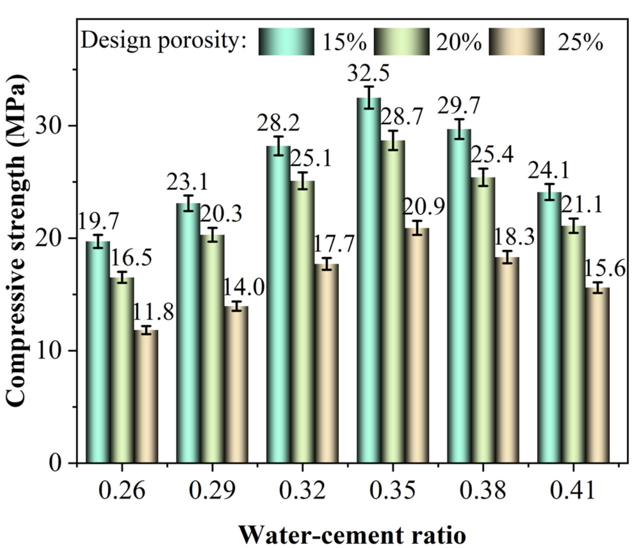

Figure 8: Compressive strength of pervious concrete.

3.3 Fitting and mix ratio design of pervious concrete

3.3.1 Permeability fitting

Figure 9 shows the effect of design porosity on the permeability of pervious concrete. The permeability of pervious concrete gradually increased with the increase of design porosity. When the water-to-cement ratio was constant, the permeability coefficient and the design porosity had a linear relationship. The regression analysis is expressed in the following equation:

$$k = k_1 x + b_1, \tag{3}$$

where k is the permeability of pervious concrete, x is the design porosity (%), and k_1 and b_1 are the slope and intercept of permeability fitting formula at different water-to-cement ratios, respectively.

All R^2 values were better than 0.991. The factors k_1 and b_1 in Eq. (3) were affected by the change of the water-to-cement ratio, as shown in Figure 10. The slope gradually decreased as the water-to-cement ratio increased, indicating that the rise of the water-to-cement ratio weakens the influence of design porosity on permeability. This can be explained by the fact that the slurry with greater fluidity is more likely to block the pores at the bottom of pervious concrete. And the number of connected pores at the bottom of pervious concrete with different design porosity does not differ significantly at larger water-to-cement ratios, so there is no obvious difference in the permeability performance.

3.3.2 Compressive strength fitting

Figure 11 shows the effect of design porosity on the compressive strength of pervious concrete. When the water-to-

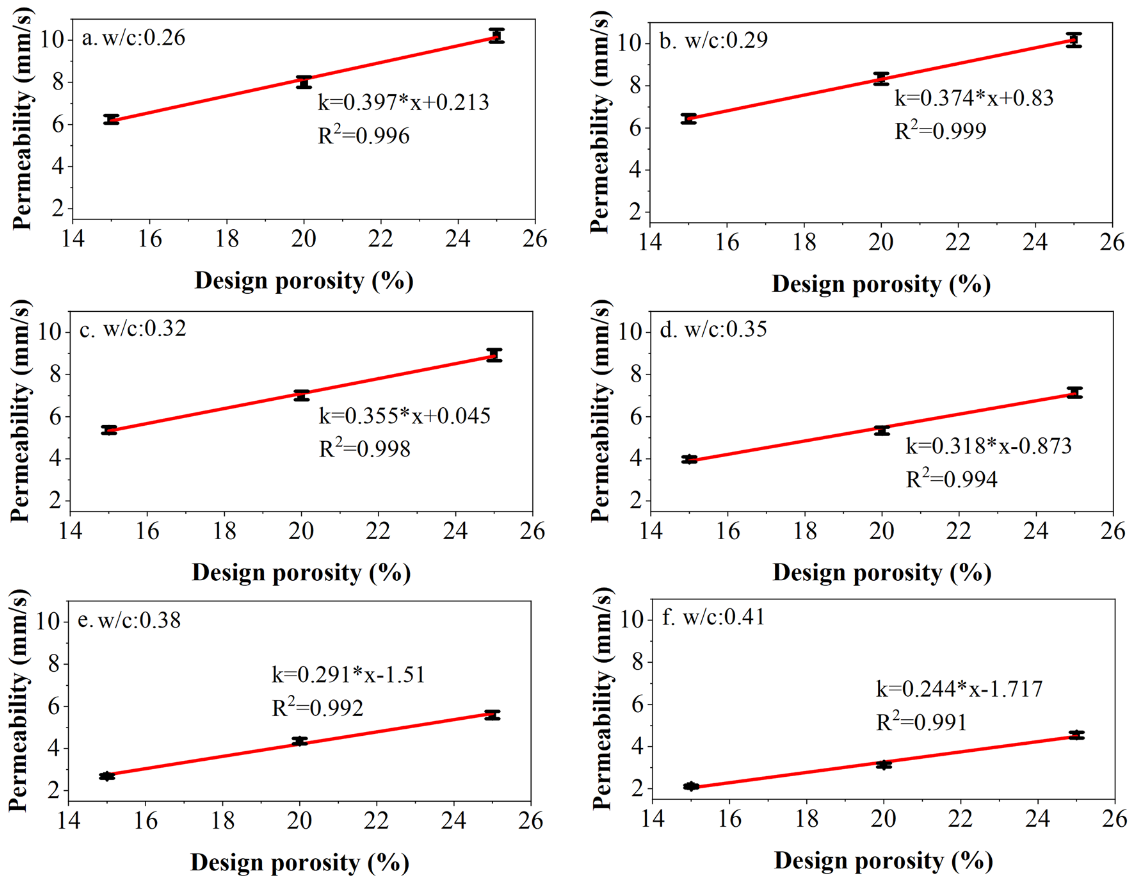

Figure 9: Effect of design porosity on the permeability of pervious concrete.

cement ratio was constant, the compressive strength of pervious concrete decreased as the design porosity increased. Studies have shown that there is a linear relationship between the porosity and compressive strength of pervious concrete [39], an exponential function relationship [40], and a cubic linear relationship [41]. Despite variations in findings, all research shows that porosity has a negative correlation with the compressive strength of pervious concrete. In

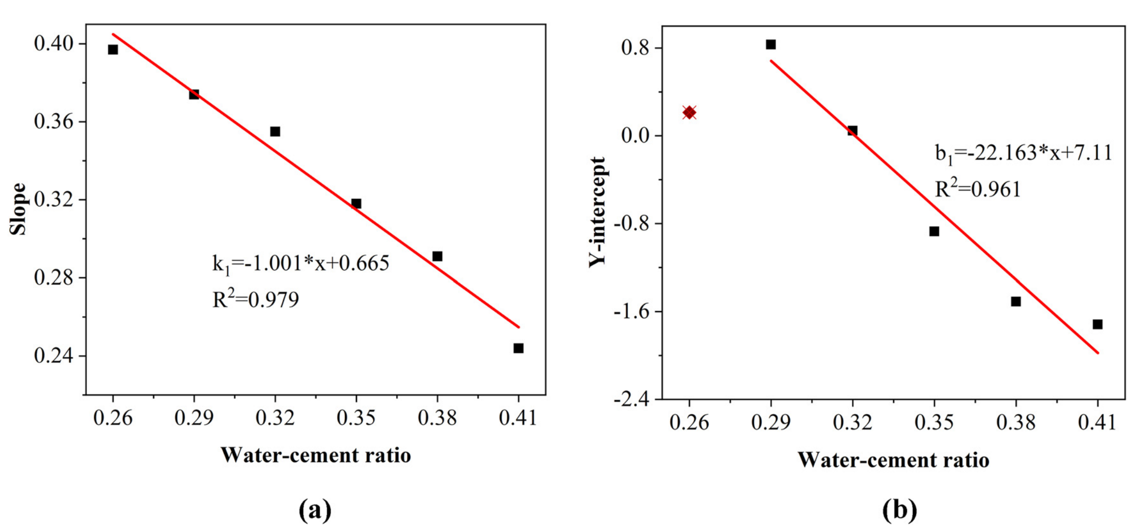

Figure: 10: Effect of the water-to-cement ratio on the permeability fitting factors: (a) slope and (b) *Y*-intercept.

this study, a linear relationship was established between compressive strength and design porosity, and all R^2 values were better than 0.942. The regression analysis is expressed in the following equation:

$$y = k_2 x + b_2, \tag{4}$$

where y is the compressive strength of pervious concrete (MPa), x is the design porosity (%), and k_2 and b_2 are the slope and intercept of compressive fitting formula at different water-to-cement ratios, respectively.

The effect of the water-to-cement ratio on the compressive strength fitting factors is shown in Figure 12. The slope and intercept of pervious concrete show a quadratic relationship with the change of the water-to-cement ratio. With the increase of the water-to-cement ratio, the slope factor first decreased and then increased, while the intercept factor first increased and then decreased. This indicates that the effect of porosity variation on pervious concrete compressive strength first increases and subsequently declines with increases in the water-to-cement ratio. Additionally, pervious concrete with lower design porosity had higher compressive strength. When the water-to-cement ratio was lower than 0.35, due to the incomplete wrapping of the coarse aggregate particles by cement slurry, the connection between the coarse aggregate particles was poor, affecting the strength development. When the water-to-cement ratio was higher than 0.35, there was a better correlation between the aggregates, but the sedimentation of the slurry reduces the strength. As a result, the effect of porosity on strength was weakened. The slope and intercept reached a minimum value of −1.16 and a maximum value of 50.56 at the water-to-cement ratio of 0.35. At this time, the pervious concrete had the maximum compressive strength.

3.3.3 Mix ratio design optimization

According to the aforementioned fitting results and based on the volume method, a method of mixed design of pervious concrete with predictive compressive strength was proposed. The method involves the following steps: (1) selecting the design strength; (2) setting the water-to-cement ratio and calculating the slope k_1 and k_2 and

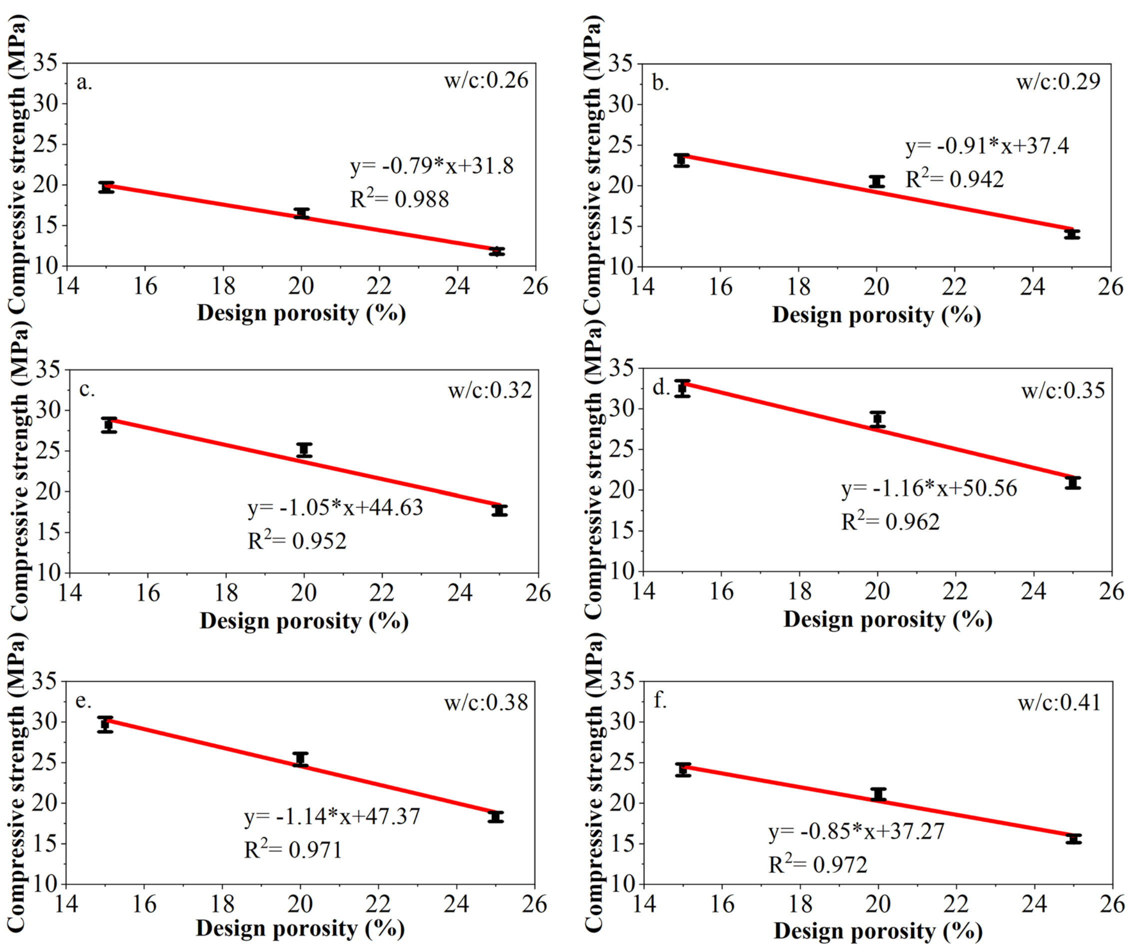

Figure 11: Effect of design porosity on compressive strength of previous concrete under different water-cement ratios (a–f).

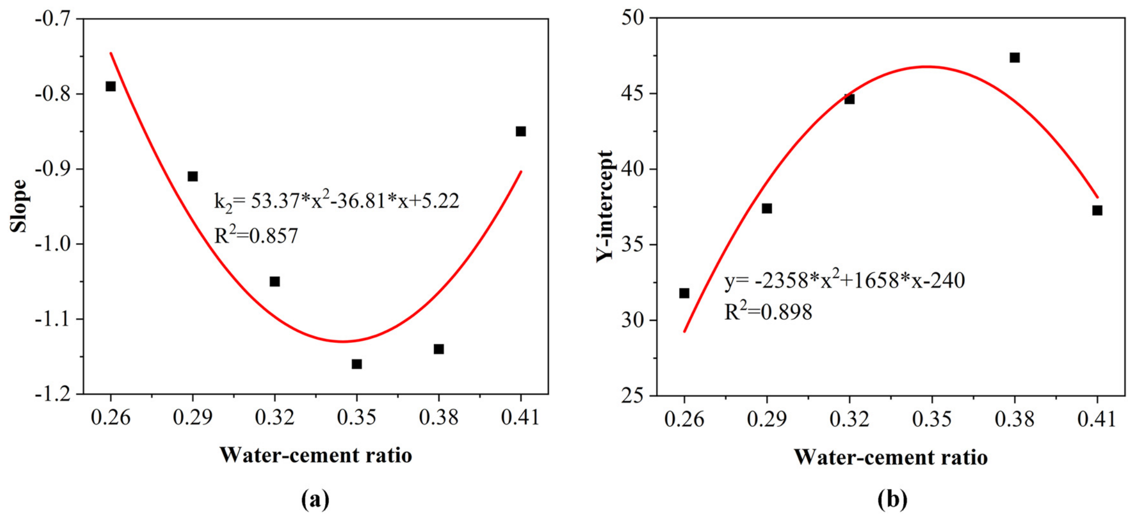

Figure 12: Effect of the water-to-cement ratio on the compressive strength fitting factors: (a) slope and (b) *Y*-intercept.

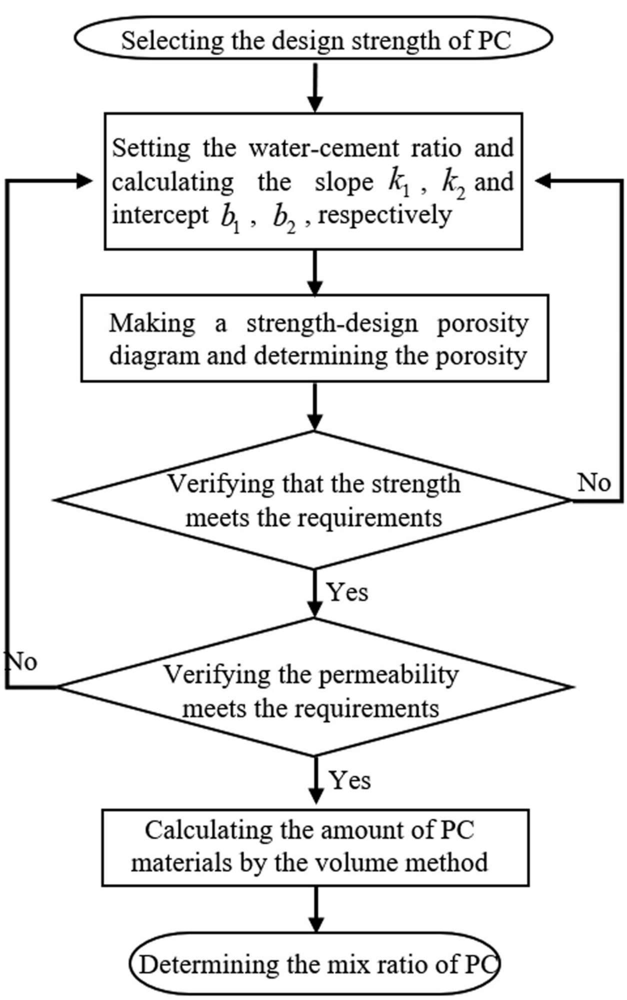

Figure 13: Flow chart for pervious concrete mix ratio design.

intercept b_1 and b_2, respectively; (3) making a strength-design porosity diagram according to Eq. (4) and determining the porosity; (4) verifying that the strength and permeability coefficient meet the desired requirements; and (5) computing the amount of pervious concrete materials required to obtain the mix ratio by the volume method. Figure 13 shows the mixed proportion design flow of the pervious concrete.

3.4 Discussions

Figure 14 shows the estimated and measured compressive strength of pervious concrete, where the C series and M

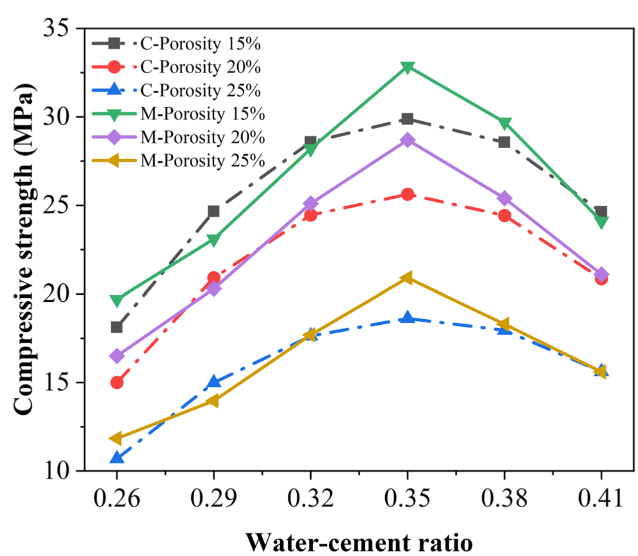

Figure 14: Estimated and measured strength of pervious concrete.

series represent the estimated strength and measured strength, respectively. The error between the estimated and measured compressive strength of the pervious concrete increased with the increase in porosity. This may be because pervious concrete with higher porosity has more complex pore characteristics. The change in the water-to-cement ratio and the complex pore structure of the pervious concrete will affect the strength change. When the design porosity was 15, 20, and 25%, respectively, the maximum errors between the estimated strength and the measured value of the pervious concrete were 8, 10.8, and 11.04%, and the average error was 5.05%.

4 Conclusion

This study researched the influence of the water-to-cement ratio on the fluidity, viscosity, and 28 days' strength of cement paste. Additionally, the influences of the design porosity and water-to-cement ratio on the mechanical properties, porosity, and permeability of pervious concrete were studied, and the test results were fitted and analyzed. The main conclusions are as follows:

1) The fluidity of cement paste first increased abruptly and then gradually as the water-to-cement ratio increased, while the viscosity first declined slowly and then rapidly. The slurry transformed from having high viscosity and low fluidity to having low viscosity and high fluidity when the water-to-cement ratio reached 0.32. The 28 days' compressive and flexural strength of the cement paste decreased linearly with increasing water-to-cement ratio, with R^2 values of 0.972 and 0.993, respectively.
2) When the design porosity was less than 25%, the permeability coefficient and porosity initially rose and then fell as the water-to-cement ratio increased. However, when the design porosity was 25%, the permeability coefficient and porosity steadily dropped as the water-to-cement ratio increased. The compressive strength of pervious concrete with various design porosities increased first and then declined as the water-to-cement ratio increased and reached the maximum value at 0.35. In this study, the maximum compressive strength and permeability coefficient of pervious concrete reached 32.5 MPa and 10.21 $mm \cdot s^{-1}$, respectively. The permeability coefficient was 3.97 $mm \cdot s^{-1}$ when the compressive strength was maximum.
3) The compressive strength of pervious concrete had a negative linear relationship with the design porosity when the water-to-cement ratio was constant, while the permeability coefficient had a positive linear relationship. The slope and intercept of the fitting connection between the permeability coefficient and the design porosity were linear with respect to the water-to-cement ratio. And the slope and intercept of the fitting relationship between the compressive strength and the design porosity were quadratic for the water-to-cement ratio. A mixed design approach that can forecast the compressive strength of pervious concrete was proposed based on the fitting relationship and volume method.

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