Mechanical properties, permeability and freeze-thaw durability of low sand rate pervious concrete

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Abstract. To improve the mechanical properties, permeability and freeze-thaw resistance of pervious concrete (PC), make the gradation more reasonable, a kind of low sand rate pervious concrete (SPC) was prepared in this study. The sand was used to replace coarse aggregate with equal volume method. The effects of sand replacement rate (0%, 5%, 10% and 15%) on the compressive strength, flexural strength, effective porosity, permeability coefficient and compressive strength loss (under the freeze-thaw cycle) of SPC were studied. The results showed that the compressive strength and flexural strength increased first and then decreased with the increase of sand replacement rate, while the effective porosity and permeability coefficient showed the opposite trend. Moreover, the compressive strength of SPC with different sand replacement rate gradually decreased as the freeze-thaw cycles test continued. After 100 freeze-thaw cycles, the compressive strength loss rate of SPC with 5% sand content is the lowest and is 6.79% lower than that control group (0% content), which indicated that the addition of sand could significantly enhance the freeze-thaw durability of SPC. Based on the experimental results, the recommended sand replacement rate is 5%.

Keywords: Pervious Concrete; Sand Replacement Rate; Permeability Coefficient; Mechanical Properties; Freeze-Thaw Durability

1. Introduction
With the rapid expansion of impervious pavements surface area, rainwater cannot flow into the ground in time, resulting in water and soil pollution, groundwater inability to supplement, urban heat island effect, etc [1-2]. Pervious concrete (PC), characterized by high water permeability, excellent air permeability, sound adsorption and noise reduction [3], is composed of interconnected porosity and aggregate skeletons. Contributed to the porous structure of PC, rainwater can penetrate into the ground, which could effectively reduce surface runoff [4] and adjust urban heat island effect and it is also a strategic resource for building sponge cities [5-6].

PC contains a small amount of fine aggregate or no fine aggregate, leaving gaps to achieve the purpose of water permeability. However, the strength of PC decreases with the increase of PC permeability [7-8]. Some scholars have reported on the strength and permeability of PC. Rizvi et al. [9] used 15%, 30%, 50% and 100% recycled concrete aggregate (RCA) instead of coarse aggregate in PC. The strength of samples with RCA content of 30% or above decreased significantly, while permeability and pore content increased. Taking steel slag as aggregate, Zhang et al. [10] studied the effect of the ratio of binder to aggregate on PC performance. The results show that increasing the ratio of binder to aggregate can improve the mechanical properties of the material, but reduce the permeability coefficient of the material.
To improve the strength of PC without affecting the permeability as little as possible, some scholars have made relevant research. Boincelli et al. [11] studied the effect of compaction energy on the porosity, drainage capacity and tensile strength of PC based on different water-binder ratios and sand replacement ratios. The results showed that a little of fine sand was added to PC, which could increase the tensile strength by 70% and the stiffness by 35%. Increasing the compaction energy can increase bulk density, reduce pore content and drainage capacity. Lori et al. [12] adopted the copper slag to replace dolomite aggregate. The results revealed when the replacement rate is 60%, the strength reached the maximum, and the compressive strength, flexural strength and split tensile strength increase by 31%, 19% and 18%, respectively. Ibrahim et al. [13] added recycled fine aggregate (RFA) into PC, resulting in an increase of 7% in compressive strength and 37% in splitting tensile strength.

Although some scholars have researched on the performance of PC, yet the permeability and mechanical properties of PC are rarely considered comprehensively. Besides, fewer studies were reported on the freeze-thaw durability of PC. In this study, the equal volume substitution method was used to study the influence of four sand replacement rates (0%, 5%, 10%, 15%) on SPC strength, water permeability and freeze-thaw durability, and the best replacement rate was obtained. It provides a reference for the engineering application and follow-up research of low-sand rate pervious concrete.

2. Materials and methods

2.1. Materials
The coarse aggregate is natural basalt coarse aggregate (4.75~9.5mm), and its basic properties are shown in Table 1. The fine aggregate is made of river sand with an apparent density of 2552 kg/m³ and a fineness modulus of 2.7. Using P.O 42.5 ordinary Portland cement, its physical properties are shown in Table 2. A polycarboxylic acid superplasticizer with a water reduction rate of 25% is used to improve the workability of the mixture.

| Particle size (mm) | Bulk density (kg/m³) | Apparent density (kg/m³) | Bulk porosity (%) | Crashed value (%) | Water absorption rate (%) | Needle-Like Particle Content (%) |
|-------------------|----------------------|--------------------------|------------------|-----------------|------------------------|-----------------------------|
| 4.75~9.5          | 1534                 | 2786                     | 44.9             | 9.7             | 1.63                   | 7.1                         |

Table 2. Physical properties of Portland cement.

| Density (kg/m³) | Specific Surface Area (m²/kg) | Setting Time (min) | Flexural Strength (MPa) | Compressive Strength (MPa) |
|-----------------|-------------------------------|-------------------|------------------------|---------------------------|
| Initial Setting | Final Setting                 | 3d 28d            | 3d 28d                 |
| 2960            | 342                           | 182 251           | 4.7 7.5                | 21.8 47.6                 |

2.2. Mixture Proportion
The coarse aggregate was replaced by four kinds of medium sand with equal volume substitution rates of 0%, 5%, 10%, and 15%; they are labeled as SPC0 to SPC15 according to test numbers.” On the basis of previous studies [14], the water-binder ratio was determined as 0.3, the designed porosity was set to 15% and the superplasticizer content was 0.5% of the cement weight. Table 3 shows the mix proportions of SPC.
Table 3. Mix ratio of SPC

| Mix ID  | Sand Replacement Rate (%) | Aggregate (kg/m³) | Sand (kg/m³) | Cement (kg/m³) | Water (kg/m³) | Superplasticizer (kg/m³) |
|---------|---------------------------|-------------------|--------------|----------------|---------------|------------------------|
| SPC0    | 0%                        | 1503.32           | 0            | 483.1          | 144.93        | 2.42                   |
| SPC5    | 5%                        | 1428.15           | 68.85        | 483.1          | 144.93        | 2.42                   |
| SPC10   | 10%                       | 1352.99           | 137.71       | 483.1          | 144.93        | 2.42                   |
| SPC15   | 15%                       | 1277.82           | 206.56       | 483.1          | 144.93        | 2.42                   |

2.3. Specimen Preparation
In this study, 60 cubic specimens with 100 × 100 × 100 mm and 12 prismatic specimens with 100 × 100 × 400 mm were fabricated by the mixing method of cement-wrapped stone and the molding method of manual tamping. After 24 hours, all specimens were demoulded and then were cured under standard conditions (temperature of 20 ± 2 °C and a relative humidity of 95%). The permeability coefficient, mechanical properties of the specimens were tested immediately after 28 days of standard curing. For freeze-thaw cycles, first cure the sample standard for 24 days, and then submerge cured for 4 days.

2.4. Test Method

2.4.1. Effective porosity. The effective porosity of SPC was determined by the drainage method, using cubic specimens with 100 × 100 × 100 mm. The calculation formula is as follows:

\[ P = \left(1 - \frac{m_2 - m_1}{\rho_w V_0}\right) \times 100\% \]  

(1)

Where \( P \) is the effective porosity (%); \( m_1 \) is the mass of the sample immersed completely in the water (g); \( m_2 \) is the saturated surface-dry mass of the sample (g); \( \rho_w \) is the water density at 20 °C (g/cm³) and \( V_0 \) is the volume of the sample (mm³).

2.4.2. Permeability coefficient. Based on the Chinese national standard [15], the permeability coefficient of SPC is determined by the constant pressure head method using 100 × 100 × 100 mm specimens. Plastic film was used to wrap the side of the specimen, and the gap between the side wall of the instrument and the upper and lower surfaces of the specimen is filled with light clay to ensure vertical seepage of water. The calculation formula of SPC permeability coefficient is as follows.

\[ k_T = \frac{QL}{AHt} \]  

(2)

Where \( k_T \) is the permeability coefficient of the sample (mm/s); \( Q \) is the water output within t time (mm³); \( L \) is the thickness of the sample (mm); \( t \) is the time (s), \( t = 300 \) s, \( H \) is the height of water head (mm), \( A \) is the bottom area of the sample (mm²).

2.4.3. Mechanical properties. Based on the Chinese national standard [16], the compressive strength and flexural strength of SPC were tested. The size of the specimens being tested is 100 × 100 × 100 mm and the experimental process of compressive strength is shown in Figure 1. The flexural strength adopted three-point bending test with the fulcrum distance of 300mm. A prismatic specimen with a size of 100 × 100 × 400 mm was used. The specific experimental process is shown in Figure 2.
2.4.4. Freeze-thaw durability. According to the national standard [17], cubic specimens with 100 × 100 × 100 mm were selected to evaluate the freeze-thaw durability of SPC by rapid freezing method. Observe the cracks and damage of the specimen every 25 freeze-thaw cycles, and test the compressive strength of the specimen.

3. Results and discussion

3.1. Effective porosity and permeability coefficient
It can be seen from Figure 3 that as the sand exchange rate increases, the effective porosity and permeability coefficient first decrease and then increase. At 10% sand replacement rate, the effective porosity and permeability coefficient reach the minimum value of 6.99% and 2.19 mm/s, respectively. When the replacement rate of sand is low (5%, 10%), the incorporation of sand improves the particle gradation of SPC. In addition, the cement mortar mixed with sand and cement slurry will further fill the gaps between the coarse aggregate piles, making the structure more compact [11], thereby reducing the porosity and permeability coefficient of the matrix. When the replacement rate is 15%, due to the increase of fine aggregate, the specific surface area increases and the workability of the mixture decreases when the amount of cement slurry remains unchanged. Therefore, under the same vibrating condition, the compactness of the structure decreases, and the porosity and permeability coefficient increase. Figure 4 shows that as the effective porosity increases, the permeability coefficient of the material also increases. Due to the impermeability of aggregate and cement paste in SPC, the water permeability is mainly derived from the effective porosity left by concrete hardening. Therefore, the greater the effective porosity of SPC, the greater the water permeability coefficient.

Figure 1. Compressive strength test.  
Figure 2. Flexural strength test.  
Figure 3. Effective porosity and permeability coefficient versus sand replacement rate.  
Figure 4. The relationship between permeability coefficient and effective porosity.
3.2. Compressive strength and flexural strength

As shown in Figures 5 and 6, the compressive strength and flexural strength of SPC increase initially and then decrease with the rise in sand replacement rate. This is because when the sand replacement rate is less than 10%, the addition of sand increases the surface friction between the coarse aggregates, fills up part of the porosity, and makes the aggregate gradation more reasonable. Thereby improving the strength of concrete. However, when the sand replacement rate continues to increase (SPC15), the amount of cement paste remains unchanged, the specific surface area of the aggregate increases, resulting in insufficient cement paste to fully wrap the aggregate, which reduces the bond strength between the cement and the aggregate of the SPC [18]. Moreover, the number of coarse aggregate that plays a major role in SPC is reduced, resulting in a decrease in strength.

It can also be seen from the figure that when the sand replacement rate is 5%, the compressive strength reaches the maximum value of 27.28MPa and the flexural strength reaches the maximum value of 5.44MPa when the replacement rate is 10%. The extremum points of the two strengths appear at different sand replacement rates. Compared with the general splitting test, the three-point bending test has the largest and most sensitive tensile stress on the bottom of the specimen during the test. When micro cracks appear, they will rapidly expand and extend to the point of load. In addition, the errors in the production and testing process of the specimens eventually lead to the phenomenon that the flexural strength of the replacement rate of 10% is 0.18 MPa larger than the flexural strength of the replacement rate of 5%.

![Figure 5. Compressive strength of pervious concrete versus sand replacement rate.](image1)

![Figure 6. Flexural strength of pervious concrete versus sand replacement rate.](image2)

3.3. Freeze-thaw cycles test

Figures 7 and 8 show that the compressive strength of all specimens decreases with the increase of freeze-thaw cycles, while the strength loss rate is opposite. After 100 freeze-thaw cycles, the compressive strength loss rate of SPC5 was the lowest, 29.25%, which was 6.79% less than SPC0, which indicates that the addition of sand into PC could improve the freeze-thaw durability of PC. Adding a small amount of sand (SPC5, SPC10) into SPC makes the structure more compact, reduces the porosity and decreases the pore solution and degrade the total frost heave force in SPC pores which results in a decrease in compressive strength loss rate. When the sand replacement rate reaches 15% (SPC15), coarse aggregate decreases and the strength of the bonding layer between aggregates decreases. Meanwhile, the increasing porosity leads to an increase in pore solution, resulting in a strong frost heave force, which results in an increase in compressive strength loss rate.
4. Conclusion
The study used the equal volume replacement method to analyze the effect of different sand replacement rates on the effective porosity, permeability coefficient, compressive strength, flexural strength and freeze-thaw durability of pervious concrete. Based on the experimental research, the following conclusions can be drawn:

- In terms of water permeability, as the sand replacement rate increases, the effective porosity and water permeability first decrease and then increase and the turning point occurs at 10% of the sand replacement rate.
- When the sand replacement rate is 5%, the compressive strength reaches the maximum value of 27.28MPa; when the sand replacement rate is 10%, the flexural strength reaches the maximum value of 5.44 MPa.
- The compressive strength loss rate of SPC gradually increased as the freeze-thaw cycles test continue. When the sand replacement was 5%, the compressive strength loss rate was lowest and the freeze-thaw resistance was the greatest.
- Considering the permeability, mechanical properties and freeze-thaw durability of SPC, the recommended sand replacement rate is 5%.

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