Study of the Permeability Coefficient of Pervious Concrete with Various Aggregate Grades

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Abstract. Pervious concrete (PC) is a kind of green and environmentally friendly material with good permeability. It has the function of relieving the pressure of urban drainage system and promoting the harmonious coexistence between human and nature. The purpose of this study was to evaluate the effect of porosity and aggregate size on the water permeability and mechanical properties of PC. Through the volumetric method, three kinds of single-grained gravel aggregates of 5~10mm, 10~15mm and 15~20mm were used to design and prepare PC with porosity of 15%, 20% and 25%. A linear fitting function and a power fitting function are found to demonstrate the correlation between the permeability coefficient and the porosity, respectively. The results showed that porosity and aggregate size are both important factors affecting the performance of PC. When the porosity is the same, the larger the aggregate size is used, the higher the permeability coefficient of PC is obtained. The permeability coefficient increases with the increase of the measured porosity. The smaller aggregate size is beneficial to increase the 28d compressive strength of PC. A power fitting function can better to characterize the correlation between the permeability coefficient and the measured porosity, and the fitting equation is \[ K_T = 121.24 \times P_{\%}^{2.39} \] \((R^2=0.97)\).

1. Introduction
With the rapid development of modern cities, many cities are covered by a large number of closed infrastructure and impervious concrete pavement, which leads to the drainage of urban rainy days can only be eliminated through urban drainage systems. The annual precipitation in some cities in China is huge, and the drainage capacity of urban drainage systems is limited, which leads to the problem of surface gathered water on rainy days [1]. PC is an ecotype concrete with a certain permeability, which can make water naturally permeable [2]. Compared with ordinary concrete, PC has larger porosity, ranging from 15% to 25% and permeability coefficient from 1 to 15 mm/s [3]. It has the advantages of water permeability, temperature and humidity regulation. Therefore, pervious concrete is of great significance for the construction of sponge cities [4].

Meng [5] prepared PC by one-time feeding method and cement-wrapped stone method respectively. The results show that mixing with cement-wrapped stone method is beneficial to improve the permeability of permeable concrete. Wang et al. [6] compared continuous gradation with single particle size gradation, pointing out that using single particle size aggregate can ensure the mechanical properties and water permeability of concrete at the same time. Zhang [7] pointed out that the performance of PC is better when the water cement ratio is between 0.24 and 0.30. Liu [8] pointed out that in the early stage of hydration and hardening, moisture maintenance can reduce the risk of cracking.

In this study, through the preparation of pervious concrete with different aggregate sizes and different designed porosities, the influence of aggregate size, porosity on its permeability and
mechanical properties is explored experimentally, and analyzed which provides a theoretical basis for the configuration of high performance pervious concrete.

2. Materials and Methods

2.1. Materials

The main experimental materials were Ordinary Portland cement P·O42.5, gravel aggregate, water and superplasticizer. The properties of Ordinary Portland cement were shown in Table 1. As shown in Figure 1, gravel aggregate was single-grain aggregate and obtained by sieving. The sizes are 5~10mm, 10~15mm and 15~20mm respectively. The physical properties of aggregate are shown in Table 2. The dosage of superplasticizer was 1% cement by mass.

![Three kinds of single-grain aggregate](image)

**Figure 1.** Three kinds of single-grain aggregate

**Table 1.** Properties of Ordinary Portland cement

| Density(kg/m3) | Setting time (min) | 28d Compressive Strength (MPa) | Cement Normal Consistency (ml) |
|---------------|--------------------|-------------------------------|-------------------------------|
|               | Initial Setting    | Final Setting                 |                               |
| 3.15          | 196                | 275                           | 52.6                          | 135                           |

**Table 2.** Physical properties of gravel aggregate

| Aggregate Size(mm) | Apparent Density(kg/m3) | Bulk Density(kg/m3) | Accumulative Porosity(%) |
|--------------------|-------------------------|---------------------|--------------------------|
| 5~10               | 2840                    | 1479                | 47.9                     |
| 10~15              | 2840                    | 1456                | 48.7                     |
| 15~20              | 2840                    | 1412                | 50.2                     |

Note: the accumulative porosity equals the ratio of the difference value with apparent density and bulk density and apparent density.

2.2. Mix Design

The pervious concrete proportion was designed by the volumetric method according to the standard [9]. The water cement ratio was 0.25 in this experiment. Aggregate size and porosity were taken as the direct influence factors in the mix design. Three ranges of 5~10mm, 10~15mm and 15~20mm, and three porosities of 15%, 20% and 25% were considered in mix designed. The mixture ratio is shown in Table 3.
Table 3. Proportion of the pervious concrete samples

| No. | Design Porosity (%) | Aggregate Size (mm) | Cement (kg/m³) | Gravel Aggregate (kg/m³) | Water (kg/m³) | Superplasticizer (kg/m³) |
|-----|---------------------|---------------------|----------------|--------------------------|--------------|------------------------|
| A1  | 5~10                | 580                 | 1479           | 145                      | 5.80         |
| B1  | 15                  | 10~15               | 594            | 1456                     | 149          | 5.94                   |
| C1  | 15~20               | 622                 | 1412           | 155                      | 6.22         |
| A2  | 5~10                | 492                 | 1479           | 123                      | 4.92         |
| B2  | 20                  | 10~15               | 506            | 1456                     | 127          | 5.06                   |
| C2  | 15~20               | 534                 | 1412           | 133                      | 5.34         |
| A3  | 5~10                | 404                 | 1479           | 101                      | 4.04         |
| B3  | 25                  | 10~15               | 418            | 1456                     | 104          | 4.18                   |
| C3  | 15~20               | 445                 | 1412           | 111                      | 4.45         |

2.3. Samples Preparation
The PC samples were prepared as follows. Firstly, the cement-wrapped stone method was used to mix the raw materials. All the aggregate and water were mixed for 30 s. Then, the cement was added and mixed for 1 min to form a gelling material to evenly cover the outer shell of the aggregate. The layered interpolation method was used to tamp the mixture. The size of the samples was 100 × 100 × 100 mm. The samples were demolded after 1d and cured for 28d. The temperature and humidity were set to 20±2 °C and 96% respectively.

2.4. Testing Methods
The compressive strength of samples was measured according to the standard [9]. The failure load was recorded and the compressive strength was calculated according to formula (1).

\[ f_{cu} = \frac{F}{A} \]  

where \( f_{cu} \) is the compressive strength of samples (MPa); \( F \) is the failure load (kN); and \( A=10^4 \text{mm}^2 \).

The internal pore of PC can be divided into closed pore and open pore. Only the open pore can make water pass through naturally. In this experiment, the porosity was measured by water balance and calculated according to formula (2).

\[ P_M = (1 - \frac{m_1 - m_0}{\rho_w V}) \times 100\% \]  

where \( P_M \) is the measured porosity (%); \( m_0 \) is the mass of the sample submerged in water (g); \( m_1 \) is the mass of the samples in the air; \( \rho_w \) is the density of the water; and \( V \) is the volume of the samples.

In this experiment, the test principle and experimental device are shown in Figure 2. The permeability coefficient can be calculated by formula (3).
where $K_T$ is the permeability coefficient (mm/s); $L=100$ mm; $Q$ is the discharged amount of water in time (mm$^3$); $H=150$ mm; $A=10^4$ mm$^2$; $t=60$ s.

3. Results and Discussion

3.1. Permeability Coefficient

The tendency between the permeability coefficient and the designed porosity at the different aggregate sizes is shown in Figure 3. The relationship between the permeability coefficient and the measured porosity is shown in Figure 4.

![Test Principle](image1)

![Experimental Device](image2)

**Figure 2.** The permeability coefficient measurement

\[ K_T = \frac{LQ}{AHt} \]  

(3)

**Figure 3.** The tendency between the permeability coefficient and the designed porosity at the different aggregate sizes

**Figure 4.** The relationship between the permeability coefficient and the measured porosity

From Figure 3, it can be concluded that the permeability coefficient of all samples with different aggregate sizes increases with the increase of designed porosity. When the designed porosity increases from 15% to 20%, the permeability coefficient increases by 52.6%~70.2%; when the designed porosity increases from 20% to 25%, the permeability coefficient increases by 77.5%~117.4%. When the designed porosity is the same, the permeability coefficient increases with the increase of aggregate size. When the aggregate size increases from 5~10 mm to 15~20 mm, the permeability coefficient increases by 14.2%~46.3%, and the effect is more obvious when the designed porosity is lower. When the aggregate size becomes larger, the bulk density becomes smaller, the contact point between the aggregates and the cement paste are less, so that the internal pore diameter is increased, the pores
tortuosity is reduced, and more connected pores appear inside, which leads to an increase in the permeability coefficient.

From Figure 4, it can be concluded that when the measured porosity is from 13.8% to 24.7%, the permeability coefficient increases from 1.08mm/s to 4.42mm/s, and all samples meet the standard for permeability coefficient greater than 1mm/s [9]. The correlation between the permeability coefficient and the measured porosity is investigated by using the linear function and the power function respectively. The fitting results are shown in Table 4.

| Regression equation     | Correlation coefficient |
|-------------------------|-------------------------|
| $K_T = 28.59P_M + 2.97$ | 0.94                    |
| $K_T = 121.24 P_M^{2.39}$ | 0.97                |

By comparing the correlation coefficient($R^2$), it can be seen that the $R^2$ of the power fitting function is larger, and theoretically, the ordinary concrete is impervious to water, so when the porosity is 0%, the permeability coefficient should also be 0mm/s, at the same time, the linear fitting function obviously cannot express the correlation between the permeability coefficient and the porosity, while the power fitting function can express it. Theoretically, the porosity and permeability coefficient do not exhibit a simple linear relationship. The $R^2$ of the power fitting function is larger. Therefore, the power fitting function can better explain the correlation between the permeability coefficient and the measured porosity.

3.2. Compressive Strength

The tendency between the compressive strength and the designed porosity at different aggregate sizes is shown in Figure 5. The relationship between the compressive strength and the measured porosity is shown in Figure 6.

![Figure 5. The tendency between the compressive strength and the designed porosity at different aggregate sizes](image)

![Figure 6. The relationship between the compressive strength and the measured porosity](image)

From Figure 5, it can be concluded that the 28d compressive strength of all the samples decreases with the increase of the measured porosity and decreases with the increase of the aggregate size. When the aggregate size increases from 5~10mm to 15~20mm, the 28d compressive strength of the samples with the same design porosity decreases by 11.8%~16.6%. When the aggregate size is decreased, the amount of the aggregate contact points is reduced in the stacked state, the cement paste coating is more uniform, the effective contact area is increased, the internal stress distribution of the structure is uniform under pressure, and the compressive strength becomes higher. On the contrary, when the aggregate size is increased, the amount of the aggregate contact points is decreased in the stacked state, the cement paste coating is relatively uneven, the effective contact area is reduced, the stress
concentration inside the structure is obvious under pressure, and the compressive strength becomes lower. When the designed porosity increases from 15% to 20%, the 28d compressive strength decreases by 10.0%~14.3%; when the designed porosity increases from 20% to 25%, the 28d compressive strength decreases by 9.8%~13.4%. As the designed porosity increases, the amount of cement paste decreases, the cement paste bonding layer becomes thinner, and the stress concentration effect is more obvious under pressure, resulting in a decrease in the 28d compressive strength of the samples. From Figure 6, it can be concluded that when the measured porosity is from 13.8% to 24.7%, the 28d compressive strength is reduced from 24.6MPa to 16.1MPa, the linear correlation coefficient is 0.80.

4. Conclusion
(1)The permeability coefficient increases with the increase of the measured porosity. Power fitting function can better characterize the correlation between permeability coefficient and measured porosity, and the result of the fitting is \( K = 121.24 \times P_m^{2.39} \) (\( R^2 = 0.97 \)).
(2)The smaller aggregate size helps to increase the 28d strength of the pervious concrete.
(3)The 28d compressive strength decreases with the increase of porosity. The 28d compressive strength and the measured porosity have a good correlation, and the result of the fitting is \( F_{cu} = -54.4 \times P_m + 30.8 \) (\( R^2 = 0.80 \)).

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