Measurement of Permeability and the Correlation between Permeability and Strength of Pervious Concrete

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Abstract: Pervious concrete has been widely used in the fields of roads, buildings, water facilities as the material of drainage structure due to the excellent permeability. However, pervious concrete have relatively lower compressive and flexural strengths as compared to conventional concrete. Strength and permeability are two important design factors for pervious concrete, but limited research is conducted on their interactional relationship. This study focuses on the balance between permeability and strength properties of pervious concrete. A series of laboratory tests are conducted to demonstrate the effects of water-cement ratio, aggregate-cement ratio and porosity on the properties of pervious concrete including strength and permeability.

Introduction

Portland cement pervious concrete, also referred to as porous concrete, is a mixture of Portland cement, uniform coarse aggregate, with either a small amount of or without fine aggregate, and water. There is a large number of through pores among the aggregate skeletons. Generally, the porosity of pervious concrete is between 15\% and 25\%, and the permeability is typically about 2~6 mm/s, up to 10mm/s (Montes et al. 2005). The primary benefit offered by pervious concretes is their ability to transport large volumes of water through the material structure.

Pervious concrete was initially utilized since it uses less cement than conventional concrete in Europe in the 19th century. The United States began to use pervious concrete not as a cheaper substitute for conventional concrete, but for its permeability characteristics in 1970s (Mulligan 2005). Due to the excellent permeability, pervious concrete has been used in controlling storm water runoff, restoring groundwater supplies, and reducing water and soil pollution (Kajio et al. 1998; Youngs 2005). The permeability, mix design and conservation methods of pervious concrete were systematically studied by Europe and the United States. Since the pervious concrete has a much higher permeability due to the presence of large interconnected pore network, the conventional methods that are used to evaluate the permeability of normal concrete are not directly applicable. To estimate the permeability, a computerized falling head permeameter system was used by Montes et al. (2006). The system registered the change in mass of the head column and the total volume flowing out of the system every second. Another permeability test was performed by Kayhanian et al. (2012) in the field using the falling head method by filling the cylinder with water and measuring the time required for water to fall the desired depth.
within permeameter tiers. While these methods are still someway insufficient, affecting the accuracy of the test, and the sidewall-leakage is the biggest problem for those testing devices.

However, pervious concretes have relatively lower compressive strengths as compared to conventional concretes. This is mainly attributed to the presence of macro sized pores and large pore volumes, and also due to the absence or minimal quantity of fine aggregates used in their proportion (Cackler et al. 2006). The low strength of conventional pervious concrete not only limits its application in heavy traffic highways but also influences the stability and durability of the structures. Therefore it is important to reveal the main factors affecting the compressive strength of pervious concrete and to find ways to improve its applicability. Jiang (2005) studied the effects of some factors such as gradation and particle size of aggregate, mass ratio of aggregate to cement, mass ratio of water to cement, admixtures and mixing process on the properties of pervious concrete including porosity, permeability and compressive strength. While limited research is conducted on the balance between permeability and strength properties of pervious concrete or their quantitative relations in certain conditions. The study is directed to address the relationship between strength and permeability of pervious concrete, with reasonably fitted curve establishing the relate performances of the pore structure.

**Development of a new pervious concrete permeability test device**

Permeability measurements of concrete specimens have been developed mostly for conventional concrete with low permeability (permeability coefficient is less than 0.01 mm/s). Sidewall-leakage is the biggest problem for the existing testing devices. This is because there exits large numbers of open pores on the surface of pervious concrete specimens; these open pores are directly connected to the container sidewall. A new permeability test device for pervious concrete is developed (Cui et al. 2015). This device (as shown in Fig. 1) can prevent the sidewall flow of specimen completely. Permeability can be got according to the Darcy's law.

![Figure 1. Permeability test device.](image-url)
Strength and permeability tests

Test materials
Coarse aggregates were composed of limestone rubbles with size between 4.75mm and 9.5mm, the physical indexes are listed in Table 1. Ordinary Portland cement was used in all prepared mixes.

<table>
<thead>
<tr>
<th>Particle size (mm)</th>
<th>Apparent density (kg/m³)</th>
<th>Stacking density (kg/m³)</th>
<th>Porosity (%)</th>
<th>Crushed value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.75–9.5</td>
<td>2664.5</td>
<td>1655</td>
<td>37.89</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Samples preparation
The method described in the authors’ previous study (Cui et al. 2015) is used in the mix design of pervious concrete.

Cement paste encapsulating aggregate method was used to mix the pervious concrete. Specimens were then made in three kinds of sizes: 100mm × 100mm × 100mm for compressive strength test, 400mm × 100mm × 100mm for flexural strength tests and φ100mm × 100mm for permeability test. Vibration molding method was used and duration of vibration was 15s. Specimens were demoulded after 24 hours, and then were placed in standard curing room.

The test target porosity ratio were 10%, 15%, 20% and 25% , and water-cement ratio were 0.32, 0.34, 0.36, 0.38 and 0.4 respectively. In tests, a total of 20 cases were studied.

Strength and permeability tests
The strength test was conducted based on China Standard Mechanical Test Methods of Plain Concrete (GB/T 50081-2002). Tests were carried out with hydraulic universal press; the loading speed was 0.5MPa/s. The average strength value of three specimens in the test was taken as a test value. The permeability tests of pervious concrete were carried out with the new developed device.

Test results and analyses
In tests, all experimental results are the average value of three repeated tests results. The relationship of the measured porosity and the target porosity was shown in Fig. 2. It confirmed that the measured porosity was very close to the target, and the test showed good accuracy.
Effects of water-cement ratio on pervious concrete strength

The variation curve of the pervious concrete strength with water-cement ratio (W/C) is shown in Fig. 3. The relationship between the strength and W/C of pervious concrete is different from that of conventional cement concrete. Decrease of the W/C does not induce a notable increase of compressive strength. There is an optimum W/C value, and when the W/C is about 0.36, both compressive strength and flexural strength of pervious concrete reach the maximum, and the porosity (P) shows little influence on the strength. As Sonebi and Bassuoni (2013) explain, when the W/C increases, a higher volume of paste that is in excess of the needed amount to encapsulate the aggregate for bonding the pervious concrete matrix is produced. The surplus paste clogs the open pore structure of pervious concrete, thus reducing the void ratio and increasing compressive strength. But when the W/C is too high, the compressive strength decreases like the conventional concrete, as too many pores due to the evaporation of water lead to the decrease of strength.

Effects of porosity on pervious concrete strength

Both the compressive strength and flexural strength decrease as the porosity increases, as shown in Fig. 4. This is because when porosity increases, less bonding points and
bonding area lead to the reduction of the strength. Meanwhile, the interactions between granules decrease. For different W/C, the curves of the compressive and flexural strengths versus measured porosity can be fitted using Lorentzian function with the goodness of fit being 0.927 and 0.839, respectively:

$$f_c = 10.156 + \frac{2566.466}{\pi \frac{10.161}{4(P - 0.453)^2 + 103.246}} \quad \text{(R}^2 = 0.946\text{)} \tag{5}$$

$$f_f = 1.979 + \frac{128.5830}{\pi \frac{21.311}{4(P + 4.904)^2 + 456.720}} \quad \text{(R}^2 = 0.835\text{)} \tag{6}$$

where $f_c$ was the compressive strength, $f_f$ was the flexural strength.

### Figure 4. Relationship between strength and porosity.

![Figure 4. Relationship between strength and porosity.](image)

(a) Compressive strength; (b) Flexural strength.

**The relationship between permeability and porosity**

As shown in Fig. 5, the permeability coefficient increases when the porosity increases, and the increasing rate is accelerating. The W/C has little influence on the permeability coefficient. The porosity increases when the amount of cement paste reduces. Then both the water channels inside the concrete and the average volume of pores increase, which make the permeability increases either. The quantitative relationship between measured porosity and permeability coefficient can be fitted using different kinds of functions as shown in Fig. 5, the permeability-porosity curve is obtained, where $K$ is coefficient of permeability (cm/s), $P$ is target porosity (%).

**Effects of aggregate-cement ratio on permeability**

Fig. 6 shows the variation of permeability with aggregate-cement ratio. Obviously, aggregate-cement ratio and permeability are positively correlated. The permeability increases when aggregate-cement ratio increases. This is because as the aggregate-cement ratio increases, the amount of cement paste reduces, leading to the increase of pores between aggregates. Meanwhile, the viscous resistance of the flow reduces when average pore size increases. As a result, W/C does not induce a notable
increase in permeability of pervious concrete until the aggregate-cement ratio become greater than 5.5. The curves family of permeability coefficient with aggregate-cement ratio is just like an inverted broom type, as shown in Fig. 6.

![Figure 5. Relationship between permeability and porosity.](image1)

![Figure 6. Relationship between permeability and aggregate-cement ratio.](image2)

**Strength-permeability curves**

The variation curves of compressive and flexural strength with permeability coefficient are shown in Fig. 7. Both the compressive and flexural strength decrease when the permeability increases, but the change rate decreases gradually. And for different W/C, the curves can be fitted using Lorentzian function with the goodness of fit being 0.927 and 0.842:

\[
\begin{align*}
{f_c} &= 12.525 + \frac{740.26}{\pi} \cdot \frac{1.673}{4(k + 0.778)^2 + 2.799} \\
{f_f} &= 3.032 + \frac{425.875}{\pi} \cdot \frac{4.939}{4(k + 3.429)^2 + 24.397}
\end{align*}
\]

(9) \hspace{1cm} (10)

where \(K\) is the coefficient of permeability.

The strength-permeability curves (as shown in Fig. 7) of pervious concrete show that the pervious concrete strength has a negative correlation with its permeability.

![Figure 7. Relationship between strength and permeability.](image3)
Implementation of the strength-permeability empirical model in the design of pervious concrete

The two important design parameters used for pervious concrete program are permeability and compressive strength. Based on the obtained empirical relationships between different parameters, especially the strength-permeability empirical model, a more simple and precise design process is developed:

1. Determine the target strength $f_c$ and permeability coefficient $K$ with the minimum standards specified the level of quality control from the engineering requirements, for example, $f_c > A$ and $K > B$.

2. Then an “effective interval” is obtained as shown in Fig. 18 using the empirical relationship between compressive strength $f_c$ and permeability coefficient $K$ according to Fig. 7. The desired range of compressive strength $f_c \in (A, C)$ and permeability $K \in (B, D)$ are gotten.

3. Obtain the porosity $P$ from the desired mean permeability coefficient $K$ using the empirical relationship between permeability coefficient $K$ and porosity $P$ according to Fig. 5.

4. Obtain the optimum water-cement ratio for the desired mean compressive strength $f_c$ and the porosity $P$ using the empirical relationship between compressive strength and water cement ratio according to Fig. 3.

5. With the known aggregate-cement ratio and the optimum water-cement ratio determined by step 4, obtain the permeability coefficient $K$, based on Fig. 6 examine whether the permeability coefficient $K$ is in the desire range.

**Conclusions**

Based on a series of tests, it is found that for pervious concrete, there is an optimum W/C unlike the conventional concrete, and in the test, when W/C equals to 0.36, the pervious concrete is the strongest. The strength-permeability empirical model of pervious concrete was established. The strength of pervious concrete decreases when the permeability increases, but the rate of reduction decreases gradually. Based on the strength-permeability empirical model, the optimum mix proportion can be determined according to the engineering requirements.
Acknowledgments
This work is supported by the National Program on Key Basic Research Project of China (973 Program) (No. 2015CB058101), the Science Fund for Distinguished Young Scholars of Shandong Province (No. JQ201416), the Natural Science Foundations of China (Nos.51479105, 51279094, 51308324 and 51379115), the Program for New Century Excellent Talents in University of Ministry of Education of China (NCET-13-0340), the Fundamental Research Funds of Shandong University (No. 2014YQ013).

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