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Parameters influencing water permeability coefficient of cracked concrete specimens

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HIGHLIGHTS

- Permeability test sets were conducted on mortar specimens with a crack.
- Tested parameters were crack type, crack width, and applied water level.
- Permeability coefficient varied with test conditions even for cracks of the same width.
- Applied pressure gradient on the test specimen differed from the total water head.
- Conditions usable in permeability experiments are proposed for minimization of errors.

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ABSTRACT

Permeability test methods have been used for measuring the permeability coefficient of homogeneous porous materials, but it has not been verified whether the methods are appropriate to evaluate permeable characteristics of cracked concrete. The objective of this study is to validate the permeability test method for cracked concrete specimens and investigate influential parameters on the test results. Intensive parametric studies have been done for samples with various crack types, crack widths and water heads. The results show that water head and crack width are the factors most influential on the permeability coefficients. It is observed that the actual pressure gradient that is applied between inlet and outlet of the specimen varies from 60% to 100% of the total water head due to the existence of head losses in the test device, which can lead to underestimation of the permeability coefficient. It is suggested that these head losses in the test system can be minimized by decreasing the total water head or adjusting the geometry of the test device.

1. Introduction

Water permeability tests for concrete have been widely used for measuring performance related to durability. In general, concrete of higher permeability is supposed to be less durable due to the presence of more pores and voids [1]. The intrinsic permeability is the capacity of a porous material to transfer liquids through a fully saturated pore network under a pressure gradient. In the field of concrete engineering, this permeability testing experiment has been conducted for many years to measure water permeability [2–4], and to investigate parameters affecting water transport in cementitious materials [5–10].

Many studies, such as those by Claisse et al. [11], and Abbas et al. [12], have been conducted on the transport properties of both air and water within un-cracked concrete material. The permeability of ordinary concrete is very low so that it is almost impossible to measure the water permeability without applying high pressure.

In comparison, a limited number of studies have been done on the permeability of cracked concrete. Tsukamoto [13] studied the water flow rate in cracked, fiber-reinforced concrete, and found that the flow rate scales to the third power of the crack width. The studies of Kermani [14], Tsukamoto and Wörner [15], and Gérard et al. [16] explored changes in permeability of concrete caused by the application of compressive or tensile stress. Wang et al. [17] and Aldea et al. [18] focused on a single crack within concrete and measured the permeability coefficient as a function of crack width. In addition, because crack width has many uncertainties, several researchers have measured the exact crack width of specimens by considering the loading- unloading effect. Some measurements have even been conducted while a load was applied [19–21].

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As the study of self-healing concrete has progressed, the water permeability test for cracked concrete has recently been used more to evaluate the performance of healing. When a crack penetrates such concrete, however, most of the leaked water is transported through the crack. Accordingly, in this case, the method and theory for measuring water permeable characteristics should be markedly different from existing methods, which have mainly been used for materials of homogenous condition [22]. Study results have shown that there are large variations of permeability, even for specimens with a similar crack width, due to the absence of standardized test methods. Currently, varieties of test methods have been used for measuring the permeability of cracked concrete.

In addition, the experimental measurements that have been reported so far do not coincide well with the theoretical predictions. Edvardsen [23] has proposed a reduction factor in order to compensate for the difference between measurements and predictions. However, the reduction factor itself shows a lot of variation, which supports that the theoretical assumptions may be incorrect or there are unknown parameters that affect the test results.

Therefore, in this study, the factors that influence the permeability of cracked concrete are examined, and the appropriateness of the permeability test method is verified for the use with cracked concrete, particularly regarding crack-width assessment. Finally, permeability test conditions are proposed that can produce consistent results.

2. Theoretical background of the permeability test

2.1. Permeability test methods

A permeability test has been widely used in various fields. Two types of methods have been generally used. Permeability of soils is measured with either constant-head, which is generally recommended for coarse-grained soils, or falling-head, which is better suited for testing fine-grained soils. For a concrete specimen without a crack, the constant head method has been used since high pressure needs to be applied on the specimen for water to pass through uncracked concrete. For cracked concrete, either the constant or falling water head test method has been used [17,24]. The constant head test has been applied for specimens having a relatively large crack width (0.1–0.4 mm) [25,26]. The falling head test has been used for specimens with a relatively small crack width (0.025–0.1 mm) [17,27]. However, this classification method is not absolute, just for the convenience and consistency of test methods.

2.2. Permeability coefficient

The flow of a fluid in porous media is governed by the well-accepted Darcy's law. According to this law, the flow rate through a porous medium is proportional to the pressure difference, which can be expressed with a water head between the two points. The proportional constant is called the permeability coefficient. Eq. (1) shows the water permeability coefficient K (mm/s) with unit pressure and unit time when static pressure is applied [22,28].

$$K = \frac{Ql}{Ah} \tag{1}$$

where Q is the flow rate through the specimen; l is the thickness of the specimen; A is the cross-sectional area of the concrete specimen; h is the drop in hydraulic head across the specimen.

This permeability coefficient can be used without modification for concrete without a crack since the water penetrates though the entire surface of the concrete specimen. However, when a specimen has a crack, most of the water is supposed to be transported through the crack. Therefore, a permeability coefficient needs to be used carefully. Generally, the area of the specimen is used for the calculation. If the shape and size of a specimen is fixed, a consistent calculation result can be obtained although there is a gap between the area defined in the equation and the area where the water really passes. To solve this problem, Yi et al. [25] modified the permeability per unit water-contact area into permeability per unit length of a crack.

2.3. Poiseuille's Law

While Darcy's law defines the water flow caused by the pressure difference, Poiseuille's Law defines the water flow that passes through internal ducts. When viscous fluid passes through an internal duct, a friction between the water and the wall of internal duct causes energy dissipation and makes a parabolic profile of the water velocity across the duct. Under this condition of flow, using the theory of laminar flow of incompressible Newtonian fluids inside a duct, the relation between flow rate and the dimension of the internal duct can be defined using Poiseuille's Law. Therefore, water flow through a crack can be idealized as water flow between two plates. Eq. (2) shows that the water flow rate Q through a crack is related to the cube of the crack width w [30].

$$Q = \frac{\Delta p b w^3}{12\mu l} \tag{2}$$

where b is a crack length, Δp is a differential water pressure between inlet and outlet of the crack.

3. Experimental plan

3.1. Test specimens

The test results of water permeability for cracked concrete are supposed to have large variations if specimens show much roughness at the crack surface. Also, the crack could have too much uncertainty such as a tortuous shape and variation in the crack width. Therefore, it is difficult to get exact information about the crack surface. To eliminate possible errors in the experiment, specimens with a constant crack width were prepared as well as specimens with a real crack (see Fig. 1).

Specimens of ideal crack shape were made as follows. Two specimens of semicircular shape were made separately. Then, the specimens were tied using a steel band after spacers of a specific thickness were put on the ends of the specimen's surface to make a crack of constant width. The external surfaces were coated using epoxy adhesive to prevent water from permeating the surface [29].

In order to make a specimen with a real crack, cylinder specimens (Φ100 × 50 mm) were prepared. They were cracked using a splitting tensile test method, and then the split specimens were tied together with spacers to a specified crack width. Since the spacers were attached on the both ends of the cracked section, the actual length of the crack was not 100 mm but about 80 mm.

After the specimens were made, the crack widths were measured using a microscopy. Fig. 2 shows the typical shapes of the cracks made. In order to measure the crack width rationally, the crack widths were measured at several locations of cracks, then averaged. The widths of ideal cracks showed low variations, but the widths of real cracks showed from 6% to 20% of CoV.

3.2. Test parameters and method

In this study, the constant head method was used. The test parameters were the water head applied, the type of cracks and the crack width in the specimens, as shown in Table 1. The water head was varied from 100 to 900 mm and the crack width varied