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Time-dependent water permeation behavior of concrete under constant hydraulic pressure

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Abstract: In the present work, a concrete permeability testing setup was designed to study the behavior of hydraulic concrete subjected to constant hydraulic pressure. The results show that when concrete is subjected to high enough constant hydraulic pressure, it will be permeated, and after it reaches its maximum permeation rate, the permeability coefficient will gradually decrease towards a stable value. A time-dependent model of permeability coefficient for concrete subjected to hydraulic pressure is proposed. It is indicated that the decrease of the permeability coefficient with permeation time conforms well to the negative-exponential decrease model.

Key words: *concrete*; *permeability*; *permeability testing setup*; *time-dependent model*

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1 Introduction

Permeation of water and consequent corrosion is one of the main causes of damage to hydraulic concrete structures. Under hydraulic pressure, concrete will be permeated and corroded by water, resulting in damage to the hardened cement paste. Permeability is thus one of the most important properties of hydraulic concrete structures. The permeability of concrete is usually expressed as the highest water pressure that the concrete can be subjected to without incurring seepage under a specified test procedure, or the height of permeating water in the concrete specimen under a given water pressure at a specified time (MWRPRC 2006). Gas permeability has also been studied in order to characterize the permeability of concrete (Sugiyama et al. 1996; Picandet et al. 2001), but very little work has been done on the behavior of concrete after it has been permeated by water. Ruan et al. (2000) studied leakage and water corrosion in a concrete panel under different water pressures and found that the permeability of the concrete decreased with time, eventually reaching a stable value. Banthia et al. (2005) and Fang et al. (2005) studied the permeability of concrete under compressive stress. However, no additional information concerning time-dependent permeation behavior of concrete has been reported.

In the present work, the time-dependent permeation behavior of hydraulic concrete was studied using cylindrical specimens and a setup designed by the authors.

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2 Experiment

2.1 Materials and specimens

Chinese P·O 32.5 cement, Grade-II fly ash, river sand with a fine modulus of 2.5, crushed limestone with the maximum diameter of 10 mm, and tap water were used to prepare the concrete specimens, with the content of ingredients in concrete mixture shown in Table 1. Six cylindrical specimens, with inner diameters of 60 mm, outer diameters of 160 mm, and heights of 160 mm, were prepared for each set of the concrete, two for water permeation tests, three for compressive strength tests and one as the spare. The specimens were cured at (20 ± 2)°C with the relative humidity (RH) > 90% for 28 days, and the compressive strengths were tested. The results are shown in Table 1.

Table 1 Content of ingredients in concrete mixture and compressive strength of specimens

Specimen set	Content of ingredient (kg/m^3)					Compressive strength (MPa)
	Cement	Fly ash	Sand	Crushed limestone	Water	
C1	192	48	652	1 324	185	19.8
C2	290	72	611	1 241	185	30.1

2.2 Testing method and data processing

A setup shown in Figure 1 was designed for water permeation tests of the concrete specimens. Each of the two open ends of the cylindrical specimen was covered with a steel plate and steel padding. There was an L-shaped hole with a diameter of 5 mm in the upper plate, as shown in Figure 1, through which the highly pressurized water from a mortar permeability testing instrument could be driven into the inner room of the cylindrical specimen, exerting hydraulic pressure on the inner wall-face of the specimen. The hydraulic pressure was adjusted with the meter on the mortar permeability testing instrument. The specimen was set in a PVC sleeve filled with water and covered with a rubber ring to prevent the water from evaporating. There was an overflow mechanism to maintain the height of the water in the sleeve. As soon as the water permeated through the cylindrical specimen to the sleeve, the water in the sleeve would overflow. The overflow water was conducted by a rubber tube into a flask, so that all the water that permeated through the cylindrical specimen could be collected and measured using an electronic balance.

Before the tests, the plate and the padding were bound to the specimen using epoxy resin mortar, and the specimen was set in a dry place for 24 h to ensure that the binding would be strong enough to withstand the testing hydraulic pressure. Then the specimen was vacuum saturated with water, so that the permeation would stabilize in a shorter period of time. Steady hydraulic pressures of 1.0 MPa and 1.5 MPa, equivalent to hydraulic heads of 100 m and 150 m and hydraulic gradients of 20 MPa/m and 30 MPa/m, were respectively exerted on the C1 and C2 specimens during the tests. The permeating water was collected as described above and the mass of the water was weighed every 12 h and converted to the average volumetric flow rate.

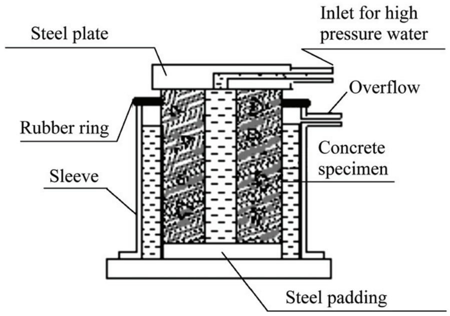

Figure 1 Setup for water permeation test of concrete specimen

Darcy's Law is often used to describe the process of water permeation of concrete in a saturated state (Picandet et al. 2008; Banthia et al. 2005; Loosveldt et al. 2002), though it may be problematic to use Darcy's Law for cement paste (Scherer et al. 2008). In the present work, the permeability coefficients of the concrete specimens at different permeation times were calculated based on the average volumetric flow rates with a modified version of Darcy's equation, as follows:

According to Darcy's Law,

$$Q = KA\frac{\Delta H}{L} \tag{1}$$

where Q is the volumetric permeation rate, K is the water permeability coefficient, A is the permeation area, ΔH is the difference in hydraulic head between the inner and the outer sides of the specimen, and L is the permeation distance.

Eq. (1) can be expressed in a differential form as Eq. (2) for cylindrical specimens:

$$Q = K\frac{2\pi rh\mathrm{d}H}{\mathrm{d}r} \tag{2}$$

where h is the height of the specimen and r is the distance from the axis of the cylindrical specimen. That is,

$$Q\frac{\mathrm{d}r}{r} = 2\pi Kh\mathrm{d}H$$

Applying integral to the equation, we obtain

$$Q\int_{r_1}^{r_2}\frac{\mathrm{d}r}{r} = 2\pi Kh\int_{H_1}^{H_2}\mathrm{d}H$$

The equation for calculating the permeability coefficient for cylindrical specimens is obtained:

$$K = -\frac{Q\ln\frac{r_1}{r_2}}{2\pi h\Delta H} \tag{3}$$

where r_1 and r_2 are the inner radius (30 mm) and outer radius (80 mm) of the cylindrical specimen, respectively.

3 Results and Discussion

3.1 Permeation and permeability

Figure 2 illustrates the change of the permeability coefficients of the two sets (C1 and C2) of cylindrical concrete specimens (two pieces for each set, labeled as C1-1 and C1-2 for example) with permeation time. It was observed, though not recorded that in the initial 3 to 4 h there was a fluctuant increase in the permeation rate. This may be ascribed to the heterogeneity of the specimens, in that different parts had different permeability coefficients over time. After the permeability coefficients reached the maximum value, it began to decrease. The time (*t*) in Figure 2 was recorded 4 h after the hydraulic pressure was applied.

There are two possible reasons for the decrease of the permeability coefficients. One is that the hardened cement paste and sand particles scoured off by hydraulic pressure lodged in and blocked the capillary pores in the concrete. The other is that the newly formed hydration products of the residual cement clinker particles blocked the capillary pores.

In this experiment, the permeability coefficients of the specimens deceased remarkably within 60 h after the highest permeability coefficients were reached, and then decreased gradually as the permeation continued.

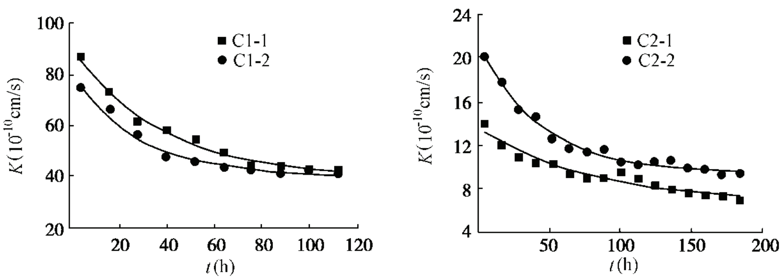

Figure 2 Permeability coefficients vs. time for concrete specimens

Compared with the C2 specimens, the C1 specimens, which had lower strength and were tested under lower hydraulic pressure, were not only permeated in a shorter amount of time, but also reached the highest permeability coefficients and a relatively stable permeation stage earlier. The reason for this is that the C1 specimens were prepared with a higher water/cement ratio and had higher porosity, which allowed the permeation to stabilize faster.

It can also be seen from Figure 2 that for both the C1 and C2 sets, experimental data from the two specimens of the same set, with the same mix proportion, are rather discrete. This shows that in the sense of permeability, concrete is a rather heterogeneous material.

3.2 Time-dependent model and stability analysis of permeation

It can be seen from Figure 2 that the permeability coefficients for all the concrete specimens changed in a similar way, decreasing over time with a similar profile. Data-fitting was conducted for Figure 2 according to Eq. (4):

$$K = K_\infty + a e^{-(t-t_0)/b} \tag{4}$$

where t is the permeation time in hours, t_0 is the time taken to reach the maximum permeability coefficients after the hydraulic pressure is applied (4 h in this experiment), K_∞ may be considered the possible stable permeability coefficient as discussed below, $K_\infty+a$ is the initial highest permeability coefficient, and $1/b$ is the permeability decay coefficient. Thus, K_∞ and a depend on the initial state and the pore structure of the specimen, while b is a function of several factors, including the composition and structure of the concrete specimen, the hydraulic head, and the temperature. The fitting coefficients are shown in Table 2 and the profiles are shown in Figure 2.

Table 2 Fitting coefficients for permeability coefficients vs. time

Specimen		K_∞	a	b	R^2
Set	Number				
C1	C1-1	39.94	46.34	36.57	0.9945
	C1-2	40.90	46.30	31.20	0.9825
C2	C2-1	6.87	6.43	72.98	0.9512
	C2-2	9.55	10.64	42.83	0.9898

Note: R is the multiple correlation coefficient.

It can be seen from Figure 2 and Table 2 that the experimental results fit Eq. (4) very well, R^2 all being greater than 0.95. The results indicate that Eq. (4) reasonably expresses the time-dependent behavior of permeation of hydraulic concrete, the permeability coefficients decreasing negative-exponentially with permeation time. As time goes on, the decrease of the permeability coefficients slows and the coefficients eventually stabilize. When time t is long enough, the second term on the right of Eq. (4) tends to be zero, so that K_∞ may be regarded as the possible stable permeability coefficient.

It should be noted that in the present work the applied hydraulic pressures were not high enough to break down the specimens. It is only under this condition that, after reaching their maximums, the permeability coefficients decrease with time. In real hydraulic concrete engineering, however, when there is a macro defect in the concrete, or when some critical hydraulic gradient is exceeded, the block effect of the particles mentioned above becomes very weak, the permeability coefficient of the concrete rises higher and higher, and the concrete eventually breaks.

As mentioned above, the permeability decay coefficient $1/b$ is a function of the applied hydraulic head. In the present work, only a given constant hydraulic head was applied to an individual concrete specimen. No clear and direct mathematical relationship can be set up between the permeability coefficient K and the hydraulic head. However, it is predictable that a higher hydraulic head will decrease the decay rate of the permeability coefficient K, and increase the magnitude of b.

4 Conclusions

According to the present work, for low or moderate strength concrete subjected to a constant hydraulic water pressure, when the hydraulic gradient is high enough that water permeates the concrete specimen but lower than some critical value which will break the specimen, the permeability of hydraulic concrete will decrease with permeation time conforming to the model $K = K_{\infty} + a\mathrm{e}^{-(t-t_0)/b}$.

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