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Water seepage flow in concrete

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HIGHLIGHTS

- The starting pressure gradient (λ) was proved exist in non-cracked concrete.
- Water would penetrate in the concrete, only when the external water pressure difference higher than the value of λ.
- External tensile stress will decrease the value of λ of the concrete.
- The modified Navier–Stokes Equation could describe the seepage law in real concrete cracks well.

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ABSTRACT

The waterproofing durability of concrete is an attentive focus in underground engineering and hydraulic structures. Water seepage law in non-cracked concrete, concrete under tension, straight smooth surface cracks and real cracks in concrete were mainly studied in this paper. And the waterproofing capacity of concrete was analyzed based on the research results. The experimental results indicated that Non-Darcy model was followed in non-cracked concrete weather it bears tensile stress or not. There existed a balance depth in the process of the water permeation. Tensile stress could change the starting pressure gradient (λ) of concrete. With the increase of tension, the λ decreased. When the concrete was cracked, water infiltrated into the concrete through cracks, the linear Darcy Law was followed in this case. To characterize the water seepage law in the real concrete cracks, two parameters τ (tortuosity of cracks) and m (toughness of cracks) were introduced into the Navier–Stokes Equation. And the result indicated the modified Navier–Stokes Equation could describe the seepage law in real concrete cracks well and the value of m in the real concrete cracks was less than 1.15 according to the experimental results.

1. Introduction

At present, a huge number of hydraulic and underground structures are being constructed in China. The durability of waterproofing of concrete in these structures has been paid much more attention. In order to predict the durability of waterproofing and design the thickness of concrete element, it is necessary to know the mathematical relationship between the depth of water seeping through concrete and the seepage time. Up till now, Darcy Model is still the main model to analyze this relationship for cement based materials which is as the typical porous media [1]. But in these years, more and more researches [2–4] have showed that Non-Darcy flow is obvious phenomenon in low permeable porous media, whose permeability coefficient is lower than 10^{-3} μm^2. Comparatively, the permeability coefficient of hardened cement paste is generally lower than 10^{-6} μm^2, and the coefficient of concrete with the compressive strength at about 30 MPa was about 10^{-7} μm^2 [5,6]. Moreover, the permeability coefficient decreases with the increase of compressive strength of concrete [7]. So the permeability coefficient of high performance concrete is much less than 10^{-3} μm^2 for low permeable porous media. Based on above analysis, it can be assumed that Non-Darcy seepage first found in other low permeable porous media may be significant in the process of water seepage in concrete. So, the first purpose of this paper is to verify Non-Darcy phenomena in concrete by experiments, and then to analyze water proofing capacity of non-cracked concrete and the influence of tensile stress.

But in real structures, concrete may be cracked. Many researches [8–15] showed that the permeability coefficient increased dramatically after concrete cracked. In order to explore the influence of crack on waterproofing durability, the seepage model in cracked concrete is extra hoped in addition to the permeability coefficient.

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2. Seepage models in non-cracked concrete

2.1. Seepage model of water in porous

We are unable to find many literatures about seepage model of water special for concrete. But for other porous media such as soil and rock, there are two models. The first is linear, that is Darcy Flow. Another is nonlinear of Non-Darcy Flow. They can be written as the following equations [4]:

$$v = \frac{Q}{A} = -\frac{k}{\mu}\nabla P \tag{1}$$

$$\begin{cases} v = \frac{Q}{A} = -\frac{k}{v}\nabla P\left(1 - \frac{\lambda}{|\nabla P|}\right) & (|\nabla P| > \lambda) \\ v = 0 & (|\nabla P| \leqslant \lambda) \end{cases} \tag{2}$$

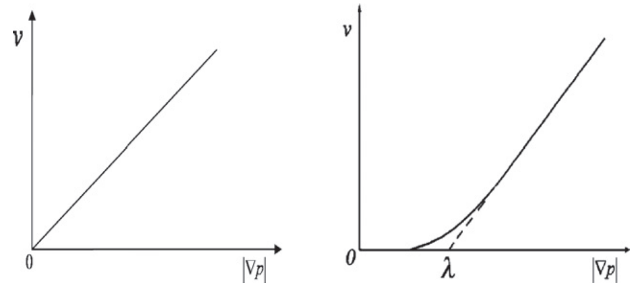
where Q is flow rate (cm^3/s), A is interface area of seepage region, v is seepage velocity (m/s), k is permeability coefficient of flow in the pore (m^2), μ is viscosity of water (Pa s), ∇P is pressure gradient (Pa/m) and λ is pressure gradient for starting flow (Pa/m).

From Eqs. (1) and (2), we can see that Linear Darcy law is the special case of the Nonlinear Darcy law when is equal to 0. The seepage model can be determined based on whether the seepage curve passes through origin of coordinates. As shown in Fig. 1a, the seepage curve passes through the origin in Darcy flow. But Fig. 1b shows a Non-Darcy flow, in which there is a starting pressure gradient of λ, only if ∇P is larger than λ, water can start flowing in porous. So, we can determine the seepage model of concrete according to the value of λ in the graph obtained from experiments.

2.2. Water seepage experiment for non-cracked concrete

Concrete is a type of porous material, water can permeate freely into the concrete and that decrease the durability of concrete. Therefore, it is possible to permeate some corrosion inhibitions from the surface of the concrete to inside the concrete due to its porosity. When the depth of the outer corrosion inhibitions penetrate into the concrete is calculated, the linear Darcy Flow is used commonly. But as the low permeable porous material, weather the concrete fit this flow rule should be verified by the experimental results. Otherwise, it will lead to the large errors in calculation.

The test device is shown in Fig. 2. The specimens are brushed by the epoxy around and then fixed on the normal concrete anti-permeability instrument. The water pressure is controlled by the instrument. When the value of water pressure is stable, the value of Q is measured at different time intervals. The permeability coefficient of concrete in different water pressure gradient can be measured by changing water pressure, and then the seepage curves can be obtained. In this experiment, a cement of 42.5 PO, a fly ash of Grade II and a S95 ground granulated blast furnace slag were used according to Chinese standard. The mix proportions for concrete samples are listed in Table 1.



(a) Linear seepage

(b) Nonlinear seepage

Fig. 1. Comparison of linear and nonlinear seepage.

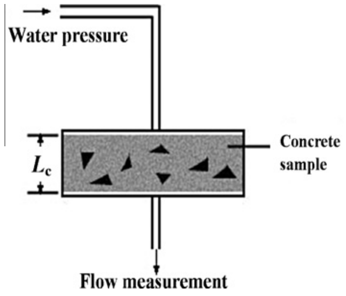


Fig. 2. Schematic diagram of test device.

The experimental results on the relationships between seepage velocity and water pressure gradient are showed in Fig. 3. It can be seen from Fig. 3 that the seepage flow curves do not pass through the origin of coordinate, there are critical pressure gradients for starting flow. This phenomenon fit to the study results of rocks [2–4]. So, in non-cracked concrete, water seepage follows Non-Darcy law as expressed in Eq. (2) and Fig. 1b. Linear fitting for the data points of Fig. 3, the starting pressure gradient λ of samples can be obtained by Eq. (2) and the results were shown in Table 2. The λ is the inherent parameter of the concrete. When the exterior water pressure gradient is lower than the value of λ, the penetration will not happened. In this case, diffusion plays an important part in penetration.

3. Seepage models in cracked concrete

During the service life, concrete structure is subject to different types of damage (mechanical, thermal, chemical, etc.). Generally service damage is not significant enough to cause an important degradation of structural concrete. However, with time, the degradation accumulates and may lead to micro-cracking resulting in permeability variations. The study purpose of this part is to research weather the Nonlinear Darcy Flow still fit to the condition of concrete with crack.

In order to make cracks with more accurate crack width, a method as shown in Fig. 4 is adopted. The concrete samples sized 100 mm × 100 mm × 50 mm were prepared, then split into two parts (50 mm × 100 mm × 50 mm) and ground on surface. Afterwards, crack is created by putting these two parts together, and crack width is controlled by a sheet of metal which thickness was known. Crack was fixed and sealed by epoxy resin in two sides. After cure of epoxy resin, the crack width was measured by crack test device (measuring accuracy: 0.02 mm). The experiment of water flowing through cracked concrete was conducted as Fig. 2. The water pressure gradient is determined by the height of the water. So this experiment limited by the height of the test location. Furthermore, the width of the crack would be under 0.5 mm, for having enough time to measure the water flowing. The experimental results are shown in Fig. 5. The cracks with six widths were investigated. And the tested results are the same order of magnitude compared with the other study results [9,10], which demonstrated the availability of this testing device. The relationships between the velocity and the water pressure gradient can be fitted as in Fig. 5 according to experimental data.

Fig. 5 demonstrated that the seepage flow curves do not pass through the origin of coordinate completely. But comparing with the curve of non-crack concrete, the pressure gradients for starting flow in crack is almost equal to zero, which means the seepage rule in crack of concrete approaches to linear Darcy Flow.

Table 1
Mix proportions of concrete (kg/m^3).

Specimen no.	Water	Cement	Fly ash	Slag	Fine aggregate	Coarse aggregate
1	177	250	70	35	779	1076
2	180	270	80	0	777	1073
3	185	250	70	35	772	1067
4	165	280	70	0	783	1082

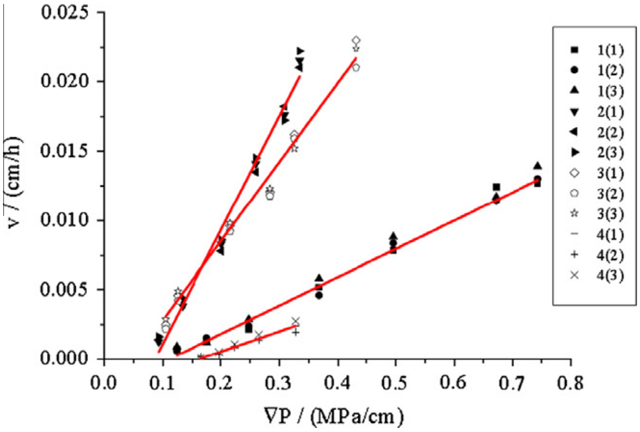


Fig. 3. The relationship between flow velocity and water pressure gradient for Samples 1–4.

Table 2
λ Values of samples.

	Sample no.			
	1	2	3	4
$\lambda/(\times 10^6\ \mathrm{Pa\ m^{-1}})$	9.94	8.76	16.01	6.63

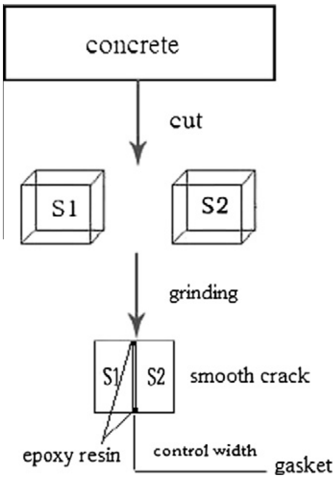


Fig. 4. Method to make a width controllable crack.

4. Water seepage in real concrete crack

4.1. Making real crack in concrete

By the above study, it is shown that water seepage in cracks plays a leading part in permeability, compared with that in non-crack concrete. There is no ideal (smooth and straight, just like making in Section 3) crack in concrete, so it is need to know how to describe this process in real concrete cracks, to calculate the water-proof durability of structure.

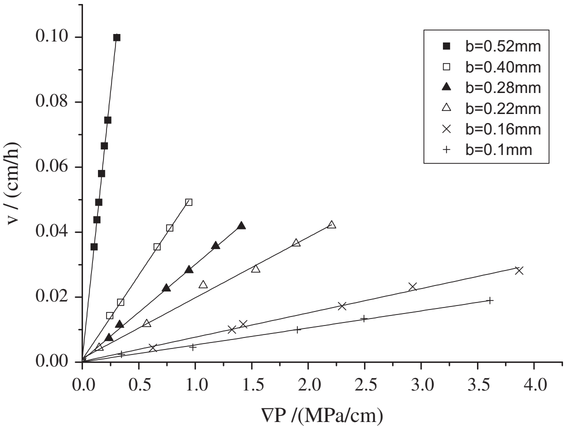


Fig. 5. Relationships between velocity of water flow and water pressure gradient for cracked concrete (b: crack width of concrete).

In order to obtain more real crack, method was carried out as follows: (1) concrete samples sized of 100 mm × 100 mm × 50 mm was prepared by cutting, (2) samples was then split into two parts by splitting test, (3) crack was created by splicing the two parts together and the surface of the samples were fixed and sealed by epoxy resin, (4) crack width was controlled by shims whose thickness was known and after cure of epoxy resin, the crack width was measured by crack test device (measuring accuracy: 0.02 mm). Schematic of specimen with crack was shown in Fig. 6(1).

4.2. Seepage model in real concrete crack

Water seepage model in ideal cracks (straight and smooth) as the Fig. 7 shown, can be expressed by the "cubic law" as shown in the follows:

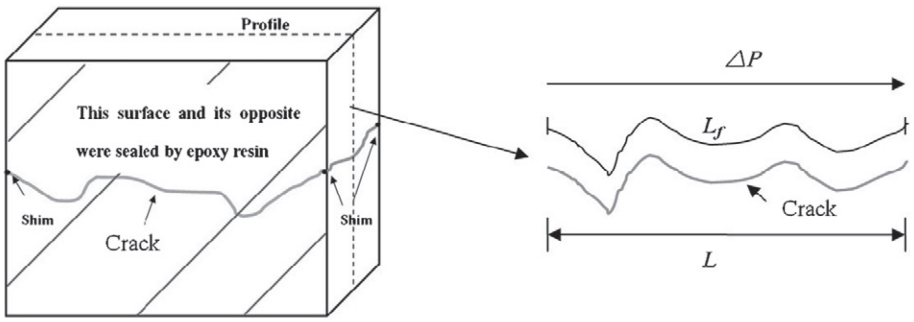
$$q = \frac{b^3}{12\mu L}\Delta p = \frac{b^3\rho g}{12\mu}\frac{\Delta H}{L} = \frac{b^3\rho g}{12\mu}J \tag{3}$$

where q is seepage velocity (L $\mathrm{m^{-1}\ s^{-1}}$), Δp is the pressure difference (Pa), b is the width of crack, ΔH *is* the height difference of equivalent water column (m), L is the straight length of crack (m), J is the hydraulic gradient (m/m), μ is the viscosity of water (Pa s).

The main difference property between the real cracks and straight smooth cracks is more tortuous and rough for the real cracks. So two parameters τ (tortuosity of crack) and m (toughness of crack) were input into Eq. (3) to modified the cubic law as shown in the following equation:

$$q = \frac{b^3\rho g}{12\mu\tau m}J \tag{4}$$

where $\tau = L_f/L$, L_f is the length of the profile of the cracks and L is the straight length of the cracks as shown in Fig. 6(2). Obviously, the profile length of crack surface (L_f) cannot be simply considered to



(1) Samples with crack

(2) Profile of crack

Fig. 6. Schematic of samples with crack and its profile. (1) Samples with crack. (2) Profile of crack.

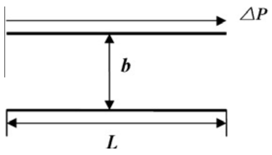


Fig. 7. Schematic of ideal crack.

Table 3
Parameters and L_f and the real cracks.

	Crack no.				
	Cr-1	Cr-2	Cr-3	Cr-4	Cr-5
b/mm	0.24	0.30	0.21	0.36	0.30
L/mm	100.5	98.0	100.0	100.0	104.0
Average L_f/mm	105.4	106.0	103.6	104.0	106.0

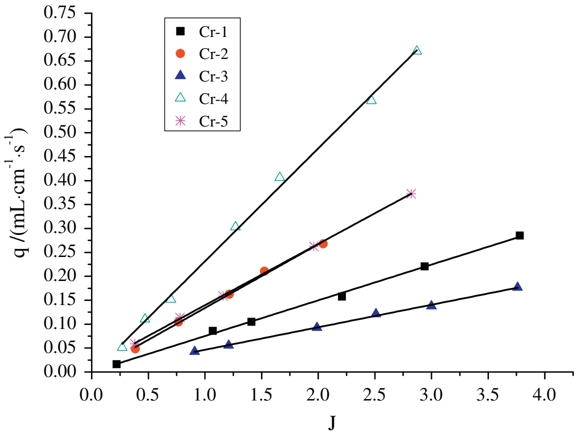


Fig. 8. Relation between seepage velocity and hydraulic gradient with different cracks.

be equal to specimen size. It was measured as soon as concrete specimen was split into two parts by press, in our research. And measuring method may be easy and feasible: attached thin cotton thread to the crack surface at different profile (it is very easy when thread and crack were wet), then, the profile length of crack surface can be obtained according to measure the length of thread. The real cracks with different widths were made and the crack profile lengths were measured to be the average of 20 test results at different depths of profiles, the parameters and the L_f of the cracks were shown in Table 3.

Table 4
Calculation results of τ and m.

	Crack no.				
	Cr-1	Cr-2	Cr-3	Cr-4	Cr-5
τ	1.05	1.08	1.03	1.04	1.06
m	1.11	1.10	1.13	1.13	1.12

Then the seepage curves of the cracks were measured and the results were as shown in Fig. 8. In Eq. (4), τ was known and then the value of m could be calculated according to Eq. (4), the calculation results were shown in Table 4.

From Table 4, we could see that the values of m were very approximately, which was also obvious with the values of τ. It may be deduced that the crack forming from the same condition has approximately crack surface roughness and roughness degree coefficient.

As a result, Cubic Law corrected by introducing the parameters of the tortuous degree and surface roughness could describe the seepage in real concrete crack. Moreover, in the paper, only crack with constant width was analyzed, the crack with variation width still need to be further studied.

5. Influence of tensile stress on seepage model in concrete

The concrete structure is always subjected to different loadings, during its service life. More researchers studied the permeability of concrete under compression stress [12–14]. Concrete is the brittle material, its tensile strength is one tenth of compression strength. Furthermore, in some structures, just as tunnel, the concrete structure subject to the tensile stress.

In order to study the influence of tensile stress on water seepage flow in concrete, a device was designed as shown in Fig. 9. The mix proportion was shown in Table 5. The tensile stress was applied on the concrete samples by four compressing springs around the sample. The samples are hollow cylinders with external dimensions Φ150 mm × 300 mm and a hole in center of Φ15 mm × 200 mm. The water would permeate through concrete with the thickness of 67.5 mm and the water infiltrated from concrete was collected.

The seepage curves of samples with different tensile stress (0 MPa, 0.5 MPa, 1.0 MPa and 1.5 MPa) were measured under 1.0 MPa, 1.2 MPa, 1.4 MPa, 1.6 MPa, 1.8 MPa and 2.0 MPa of water pressure respectively, which corresponds to the water pressure gradient of 0.148 MPa/cm, 0.178 MPa/cm, 0.207 MPa/cm, 0.237 MPa/cm, 0.267 MPa/cm and 0.296 MPa/cm respectively. And the experimental results on the relationships between seepage velocity and water pressure gradient are showed in Figs. 10–12. From the experimental results, the seepage flow curves did not pass

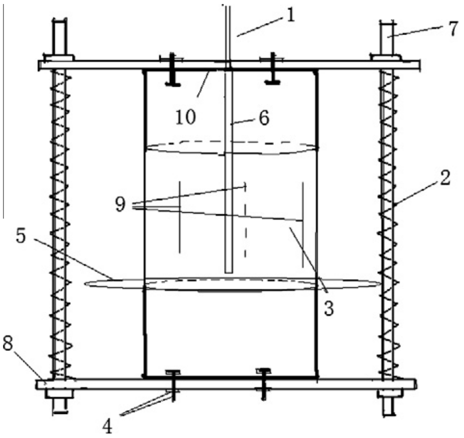


Fig. 9. Test equipment (1-copper ripe, 2-sprint, 3-sample, 4-bolts, 5-collect reservoir, 6-inner core, 7-steel tube, 8-steel plate, 9-strain gauge, 10-seal ring).

Table 5
Mix proportion of concrete for tension (kg/m^3).

No.	Water	Cement	Fly ash	Slag	Fine aggregate	Coarse aggregate
1	177	250	70	35	779	1076
2	185	250	70	35	772	1067
3	165	280	70	0	783	1082

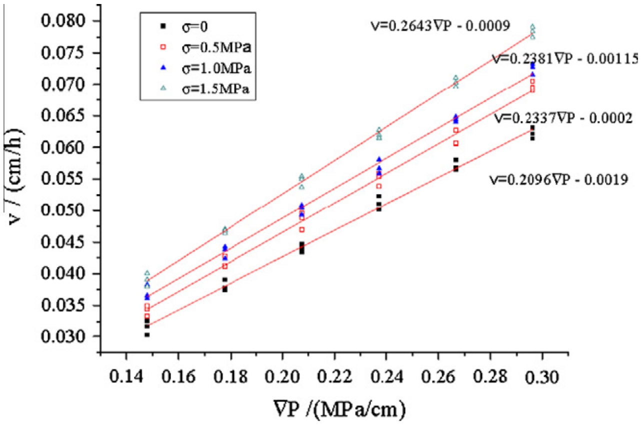


Fig. 10. Relationship between seepage velocity and water pressure gradient of No. 1 samples.

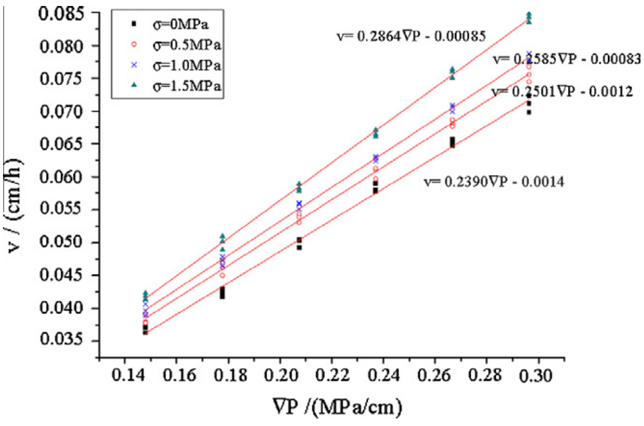


Fig. 11. Relationship between seepage velocity and water pressure gradient of No. 2 samples.

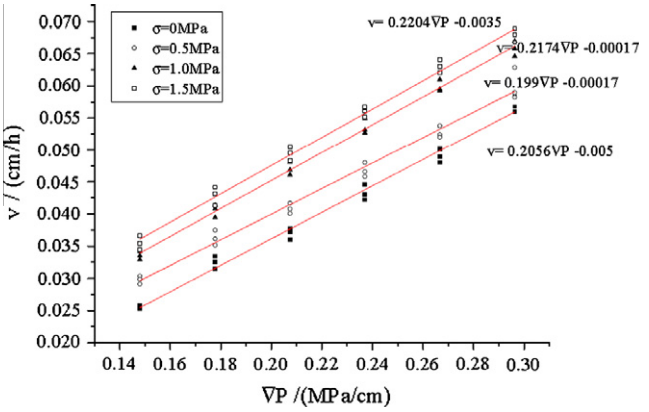


Fig. 12. Relationship between seepage velocity and water pressure gradient of No. 3 samples.

through the origin of coordinate and the λ also existed in the concrete when it under the external tensile stress. Furthermore, with the increase of the tension, the λ decreased, which mean external stress can change the λ of concrete and the seepage in non-cracked concretes whether it bears the stress or not followed nonlinear Darcy Law. But all the experimental dates were got under the 1.5 MPa tensile stress for above this stress the samples would break. When the samples broke, the v increased extremely. Compared to the non-crack samples, the λ of samples decreased by 65.8%, 62.5% and 67.7% under the 1.5 MPa tensile stress. So external stress was an important element should be considered into the design of engineering structures.

6. Analysis on waterproofing capacity of non-cracked concrete based on nonlinear flow

According to above research results, through crack is not allowed for water-proofing concrete even if the crack width is as small as 0.1 mm. The influence of tensile stress before the ultimate stress could be ignored. As for non-cracked concrete, its waterproofing capacity may attributed to the existence of starting pressure gradient of λ. When steady seepage of water is occurring in test device (see Fig. 2), Eq. (2) can be changed to:

$$v = \frac{Q}{A} = \frac{k_c}{\mu}\left(\frac{\Delta p}{L_c} - \lambda\right) = \frac{k\phi}{\mu}\left(\frac{\Delta p}{L_c} - \lambda\right) \tag{5}$$

where Q is flow rate (m^3/s), Δp is pressure different, A is sectional area of sample (m^2), ϕ is porosity, L_c is sample thickness (m), k_c is permeability of concrete. These parameters could be obtained from the test data in Fig. 3 and the results were listed in Table 6.

Obviously, $k = k_c/\phi$. The porosity was determined by the weight loss of saturated concrete after heated at 105 °C for 48 h. The test results are listed in Table 6. So, λ can be calculated according to Eq. (5).

Combined with continuity equation of incompressible fluid (considering that water pressure is not extra high in experiment, media can be seen as incompressible media), the control equation

Table 6
Calculated starting pressure gradient for Samples 1–4.

Sample no.	ϕ/(%)	k_c/(m^2)	k/(m^2)	λ/(Pa m^{-1})
1	14.12	5.30×10^{-19}	3.74×10^{-18}	9.94×10^{6}
2	14.30	2.28×10^{-18}	1.59×10^{-17}	8.76×10^{6}
3	14.04	4.28×10^{-19}	3.05×10^{-18}	1.60×10^{7}
4	14.31	1.72×10^{-18}	1.22×10^{-17}	6.63×10^{6}

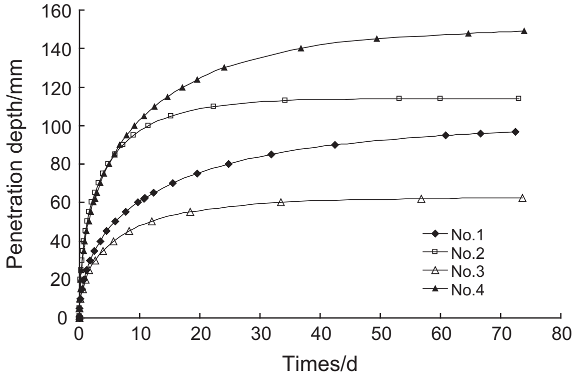


Fig. 13. The relation between infiltration depth and infiltration depth.

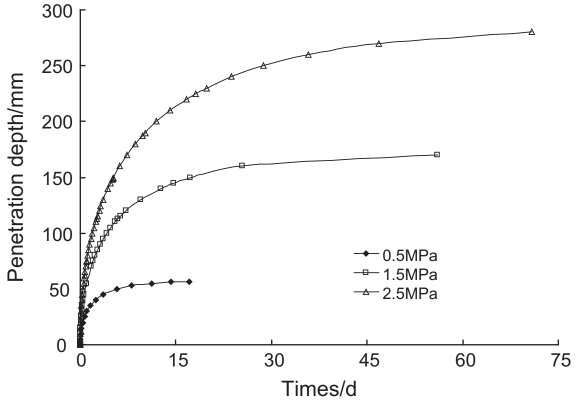


Fig. 14. Effect of water pressure on infiltration for Sample 2.

for one-dimensional permeation of water in concrete can be written as Eq. (6).

$$\begin{cases} \frac{d^2p}{dx^2} = 0 \\ v = -\frac{k}{\mu}\left(\frac{dp}{dx} + \lambda\right), \quad \left|\frac{dp}{dx}\right| > \lambda \\ v = 0, \quad \left|\frac{dp}{dx}\right| \leqslant \lambda \end{cases} \tag{6}$$

From Eq. (6), the relation between time and infiltration depth can be expressed as:

$$-\frac{\mu}{k\lambda}\left[S_{(t)} + \frac{P_0}{\lambda}\ln\left(\frac{k}{\mu}P_0 - \frac{k}{\mu}\lambda S_{(t)}\right)\right] = t - \frac{\mu P_0}{k\lambda^2}\ln\left(\frac{k}{\mu}P_0\right) \tag{7}$$

where P_0 is water pressure; t is time and $S_{(t)}$ is infiltration depth, (dp/dx) is water pressure gradient.

The relation between filtration depth and times of Samples 1–4 under 1 MPa water pressure can be calculated by Eq. (7) and shown in Fig. 13.

As shown in Fig. 13, there was a balance depth in the process of water infiltration (i.e. infiltration will stop when water's pressure gradient equals starting pressure gradient of concrete). Furthermore, the infiltration balance depth was determined by starting pressure gradient, it increased with decreasing of starting pressure gradient. So, the lower the starting pressure gradient of concrete, the thicker the balance depth is. But these depths are from 60 mm to 160 mm as shown in Fig. 13, which are much smaller than the thickness of concrete element for waterproof.

The effect of water pressure on infiltration was analyzed in Fig. 14 (take Sample 2 as an example). Even for concrete with a high water-binder ratio as Sample 2, the balance depths are from 50 mm to 300 mm when water pressure extends from 0.5 MPa to 2.5 Mpa as shown in Fig. 14. So, non-cracked concrete possesses very nice waterproofing capacity.

7. Conclusions

In the process of water seepage in non-cracked concrete, the Non-Darcy model was followed and the starting pressure gradient provided a balance depth in the process of the water permeation. Because of the existence of this starting pressure, common concrete without penetration crack demonstrated a satisfied waterproofing capacity.

The water seepage in concrete before ultimate tensile stress was also following the nonlinear Darcy Law. Tensile stress could change the starting pressure gradient (λ) of concrete. With the increase of tension, the λ decreased. So tensile stress was an important element would be considered in the design of water-proofing concrete.

Comparatively, the water flow in concrete cracks follows linear Darcy Law even though the crack width is as small as 0.1 mm. So, through crack is not allowed for waterproofing concrete.

For the real cracks in the concrete, two parameters τ (tortuosity of cracks) and m (toughness of cracks) were considered. And the modified Navier–Stokes Equation could describe the seepage law in real concrete cracks well. The value of m in the real concrete cracks was less than 1.15 according to the experimental results.

Acknowledgment

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