WATER PERMEABILITY OF CONCRETE

Bei Huang(1), Chunxiang Qian(1), Yujiang Wang(1), Miao Wu(1)

(1) School of Materials Science and Engineering, Southeast University, China

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 and real cracks in concrete were mainly studied in this paper. The experimental results indicated that Non-Darcy model was followed in non-cracked concrete whether it bears tensile stress or not. When the starting pressure gradient ($\lambda$) equaled to pressure gradient $\nabla P$, the process of penetrate stopped. There existed a balance depth in the process of the water permeation. With the increase of tension, the $\lambda$ decreased. To characterize the water seepage law in the real concrete cracks, two parameters $\tau$ (tortuosity of cracks) and $m$ (roughness 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.

Key words: concrete; water seepage; tension; cracks

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 $10^{-3}\mu m^2$. Comparatively, the permeability coefficient of hardened cement paste is generally lower than $10^{-5}\mu m^2$, and the coefficient of concrete with the compressive strength at about 30MPa was about $10^{-7}\mu m^2$ [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 $10^{-3}\mu m^2$ 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 [8-14] 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.

2. SEEPAGE MODELS IN NON-CRACKED CONCRETE

2.1. Seepage model of water in pore

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 non-linear of Non-Darcy Flow. They can be written as equation (1) and (2) respectively [4].

\[
Q = -\frac{k}{\mu} \nabla P \quad \text{(1)}
\]

\[
\begin{cases}
  v = \frac{Q}{A} = -\frac{k}{\mu} \nabla P \left(1 - \frac{\lambda}{|\nabla P|}\right) & (|\nabla P| > \lambda) \\
  v = 0 & (|\nabla P| \leq \lambda)
\end{cases} \quad \text{(2)}
\]

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\(^2\)), \( \mu \) is viscosity of water (Pa·s), \( \nabla P \) is pressure gradient (Pa/m) and \( \lambda \) is pressure gradient for starting flow (Pa/m).

![Figure 1: Comparison of linear and nonlinear seepage](image)

From eq. (1) and (2), we can see that Linear Darcy law is the special case of the
Nonlinear Darcy law when $\lambda$ 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.1 (a), the seepage curve passes through the origin in Darcy flow. But Fig.1 (b) shows a Non-Darcy flow, in which there is a starting pressure gradient of $\lambda$, only if $\nabla p$ is larger than $\lambda$, water can start flowing in porous. So, we can determine the seepage model of concrete according to the value of $\lambda$ in the graph obtained from experiments.

2.2. Water seepage experiment for non-cracked concrete

The test device is shown in Fig.2, 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.

![Figure 2: Schematic diagram of test device](image1)
![Figure 3: The relationship between flow velocity and water pressure](image2)

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. So, in non-cracked concrete, water seepage follows Non-Darcy law as expressed in Eq. (2) and Fig.1 (b). Linear fitting for the data points of Fig.3, the starting pressure gradient $\lambda$ of samples can be obtained by equation (2) and the results were $9.94 \times 10^6$ Pa·m$^{-1}$, $8.76 \times 10^6$ Pa·m$^{-1}$, $16.01 \times 10^6$ Pa·m$^{-1}$, $6.63 \times 10^6$ Pa·m$^{-1}$ respectively.

### Table 1: Mix proportions of concrete (kg/m$^3$)

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Water</th>
<th>Cement</th>
<th>Fly Ash</th>
<th>Slag</th>
<th>Fine aggregate</th>
<th>Coarse aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>177</td>
<td>250</td>
<td>70</td>
<td>35</td>
<td>779</td>
<td>1076</td>
</tr>
<tr>
<td>2</td>
<td>180</td>
<td>270</td>
<td>80</td>
<td>0</td>
<td>777</td>
<td>1073</td>
</tr>
<tr>
<td>3</td>
<td>185</td>
<td>250</td>
<td>70</td>
<td>35</td>
<td>772</td>
<td>1067</td>
</tr>
<tr>
<td>4</td>
<td>165</td>
<td>280</td>
<td>70</td>
<td>0</td>
<td>783</td>
<td>1082</td>
</tr>
</tbody>
</table>
3. WATER SEEPAGE IN REAL CONCRETE CRACKS

3.1 Making real crack in concrete

There is no ideal crack in concrete, and in order to obtain more real crack, method was carried out as follows: (1) samples was split into two parts by splitting test,(2)crack was created by splicing the two parts together and the surface of the samples were fixed and sealed by epoxy resin,(3) 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.4.

![Figure 4: Schematic of samples with crack and its profile](image)

3.2 Seepage model in real concrete crack

Water seepage model in ideal cracks (straight and smooth) can be expressed by the “cubic law” as shown in the follows[2]:

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

Where \( q \) is seepage velocity (L·m^{-1}·s^{-1}), \( \Delta p \) is the pressure difference (Pa), \( b \) is the width of crack, \( \Delta H \) is the height difference of equivalent water column (m), \( L \) is the straight length of crack (m), \( J \) is the hydraulic gradient (m/m), \( \mu \) 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 \( \tau \) (tortuosity of crack) and \( m \) (roughness of crack) were input into equation (3) to modified the cubic law as shown in equation(4).

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

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.4 (2). Obviously, the profile length of crack surface (\( L_f \)) can’t be simply considered to be equal to specimen size. It was measured as soon as concrete specimen was split into two parts , 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 2.

Table 2: Parameters and $L_f$ and the real cracks

<table>
<thead>
<tr>
<th>Crack No.</th>
<th>Cr-1</th>
<th>Cr-2</th>
<th>Cr-3</th>
<th>Cr-4</th>
<th>Cr-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$/mm</td>
<td>0.24</td>
<td>0.30</td>
<td>0.21</td>
<td>0.36</td>
<td>0.30</td>
</tr>
<tr>
<td>$L$/mm</td>
<td>100.5</td>
<td>98.0</td>
<td>100.0</td>
<td>100.0</td>
<td>104.0</td>
</tr>
<tr>
<td>Average $L_f$/mm</td>
<td>105.4</td>
<td>106.0</td>
<td>103.6</td>
<td>104.0</td>
<td>106.0</td>
</tr>
</tbody>
</table>

Then the seepage curves of the cracks were measured and the results were as shown in fig.5. In Equation (4), $\tau$ was known and then the value of $m$ could be calculated according to Equation (4), the calculation results were shown in Table 3.

Table 3: Calculation results of $\tau$ and $m$

<table>
<thead>
<tr>
<th>Crack No</th>
<th>Cr-1</th>
<th>Cr-2</th>
<th>Cr-3</th>
<th>Cr-4</th>
<th>Cr-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$</td>
<td>1.05</td>
<td>1.08</td>
<td>1.03</td>
<td>1.04</td>
<td>1.06</td>
</tr>
<tr>
<td>$m$</td>
<td>1.11</td>
<td>1.10</td>
<td>1.13</td>
<td>1.13</td>
<td>1.12</td>
</tr>
</tbody>
</table>

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.

4. INFLUENCE OF TENSILE STRESS ON SEEPAGE MODEL IN CONCRETE

In order to study the influence of tensile stress on water seepage flow in concrete, a device was designed as shown in Fig.6. The tensile stress was applied on the concrete samples by four compressing springs around the sample. The samples are hollow cylinders with external dimensions Φ150mm×300mm and a hole in center of Φ15mm×200mm. The water would permeate through concrete with the thickness of 67.5 mm and the water infiltrated from concrete was collected.

![Figure 6: Test equipment](image)

(1-copper pipe, 2-spring, 3-sample, 4-bolts, 5-collection reservoir, 6-inner core, 7-steel tube, 8-steel plate, 9-strain gauge, 10-seal ring)

The seepage curves of samples with different tensile stress were measured under 1.0MPa, 1.2MPa, 1.4MPa, 1.6MPa, 1.8MPa and 2.0MPa of water pressure respectively, which corresponds to the water pressure gradient of 0.148MPa/cm, 0.178MPa/cm, 0.207MPa/cm, 0.237MPa/cm, 0.267MPa/cm and 0.296MPa/cm respectively.

![Seepage curve](image)

(a) NO.1 samples
Figure 7: Relationship between seepage velocity and water pressure gradient

And the experimental results on the relationships between seepage velocity and water pressure gradient are showed in Fig.7. From Fig.7, we can see the seepage flow curves do not pass through the origin. The starting pressure gradient also exists in the concrete when it is under the external tensile stress. Furthermore, with the increase of the tension, the $\lambda$ decreased, which means external stress can change the $\lambda$ of concrete and the seepage in non-cracked concretes whether it bears the stress or not follows nonlinear Darcy Law.

5. CONCLUSION

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 ($\lambda$) of
concrete. With the increase of tension, the $\lambda$ decreased. So tensile stress was an important element would be considered in the design of water-proofing concrete.

For the real cracks in the concrete, two parameters $\tau$ (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.

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