NUMERICAL STUDY ON CONTROLLING DIFFUSIVITY OF CONCRETE BY PRESTRESSING

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Abstract: This paper presents the results of numerical simulation of diffusivity of uncracked concrete under compressive and tensile stresses, which are compared with test results. Both results indicate that the diffusivity of uncracked concrete depends on the stress level, which is ignored in present durability design and that prestressing would enhance durability better than the present design considers.

Keywords: Diffusivity, prestressing, durability design, numerical simulation

1. INTRODUCTION

Prestressed concrete has an advantage to non-prestressed concrete for cracking control. Durability requirement is a primary reason for cracking control. Design codes usually provide a limit of crack width (or allowable crack width) for cracking control. The most strict crack width limit is 0 mm; namely no crack allowed. This means that it would be the same for durability if no crack would occur no matter how much stress would act in concrete.

Recent studies, however, disclose that shielding property of concrete, such as chloride ion diffusivity and water permeability, varies with stress acting in concrete (Sakoi and Horiguchi 2006; Banthia and Bhargava 2007). The shielding property is enhanced with compressive stress for stress levels less than 20 to 30% of the compressive strength, but is deteriorated with compressive stress for greater stress levels. On the other hand the shielding property is deteriorated with tensile stress consistently even for stress levels less than the tensile strength. This implies that the advantages of prestressed concrete to non-prestressed concrete would be better than the present design code’s saying.

This paper presents the numerical simulation results of shielding property varying under varying stresses and discusses the durability enhancement by prestressing.

2. EXPERIMENTAL FACTS ON WATER DIFFUSIVITY OF CONCREE

2.1 Relationship between Permeability Coefficient through Crack and Crack Width

A few experimental works have been done to evaluate the effect of cracking on permeability of concrete by artificially formed crack of designed widths. For example, Aldea et al. (1999; 2000) carried out a series of experiments to investigate the water permeability of concrete with different crack widths ranging from 17 to 350 microns, which were induced by feedback-controlled splitting tests. The experimental results indicated that water permeability of cracked material significantly increases with increasing crack width. Zhang et al. (2009; 2010) experimentally investigated the effect of cracking on water penetration into concrete by means of neutron radiography. It was observed that when the surface of the sample is put in contact with water, the crack, with width of about 0.35 mm, is filled immediately with water, even after only one minute (see Fig. 1).

The permeability coefficients of cracked and fully saturated concrete samples collected from Adlea et al. (1999; 2000) and Wang et al. (1997) are presented in Fig. 2, among which Aldea et al. (1999) performed tests on specimens with two thicknesses of 25 and 50 mm and thickness of the samples was proved to have little effect upon the permeability coefficient. Specially, it should be pointed out that the crack widths shown in Fig. 2 are the real values during permeability test, including those measured after unloading (Wang et al. 1997; Aldea et al. 1999) and those detected under load (Adlea et al. 2000). One of the goals of the tests is to establish a relationship between the permeability coefficient of water through cracks and crack width.

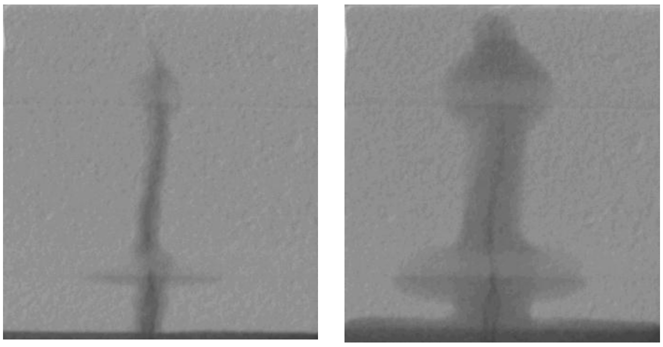

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Fig. 1 Water penetration into a single crack (Zhang et al. 2009)

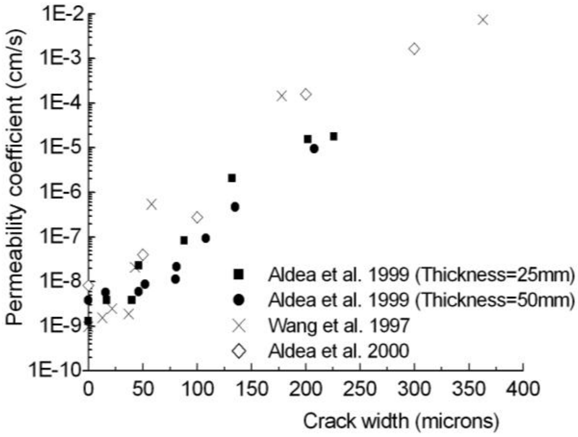


Fig. 2 Cracking effect on permeability of concrete

In order to construct a relationship between water permeability coefficient and crack width, the experimental data collected from literatures are normalized in terms of their corresponding uncracked material, which are shown in Fig. 3. The proposed formulation to approximate these data is as follows:

$$\frac{\log \frac{K_{cr}}{K_0}}{\log \frac{K_{\max}}{K_0}} = \alpha_0 + \frac{1-\alpha_0}{1+\left(\frac{w_{cr,\max}-w_{cr}}{w_{cr,\max}-w_{cr,th}}\right)^m} \tag{1}$$

in which K_0, K_{cr} and $K_{\max}$ are the permeability coefficients for the uncracked material, through cracks of any given width and the maximum width, respectively; $w_{cr,\max}$ is the maximum crack width beyond which there is no further effect on the water permeability, and herein it is set as 0.4 mm referred to the test design; $w_{cr,th}$ is the crack width up to which cracking has little effect on concrete permeability. The value of $w_{cr,th}$ is in a quite large range according to different studies from 0.018 to 0.08 mm. Therefore, in this study, it is given a value of 0.05 mm. w_{cr} is the crack width in mm; α_0 and m are constants to be determined by data regression. By curve fitting in terms of the available data, the constants in the equation is determined as α_0=-0.75 and m=2 and the obtained curve is presented in Fig. 3 to compare with test results.

Although absorption of water by unsaturated hardened concrete has been recognized as the main transport mechanism for aggressive agents to penetrate into concrete under the wetting-drying condition, currently there is no sufficient experimental data for establishing a relationship of the capillary water diffusivity coefficient D_w as a function of crack width. Ožbolt et al. (2010) recently argued the logical correlation between permeability and water diffusivity for the damaged (cracked) concrete. It was proved that the effect of cracking on the relative increase in water diffusivity is considered to be the same as the relative increase of permeability of concrete to water. Therefore, the relationship represented by Eq. (1) will be used to account for the increasing effect of various crack width on water diffusivity of concrete.

2.2 Effects of Stress Level on Permeability

Banthia and Bhargava (2007) reported an experimental study on the influence of compressive stress on water permeability of plain and fiber reinforced concrete. In this research, the water permeability was measured under stress to avoid the closing of internal cracks of concrete. The results indicated that when the applied stress is lower than a threshold value, proposed as 30% of the ultimate strength of concrete in compression, the plain concrete showed a decrease in the permeability, but beyond this level of stress, a significant increase in permeability was observed.

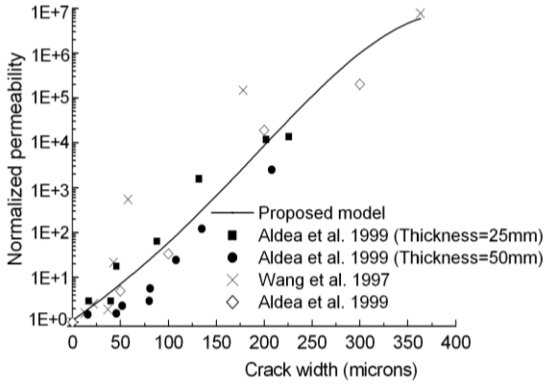


Fig. 3 Relationship between normalized permeability and crack width

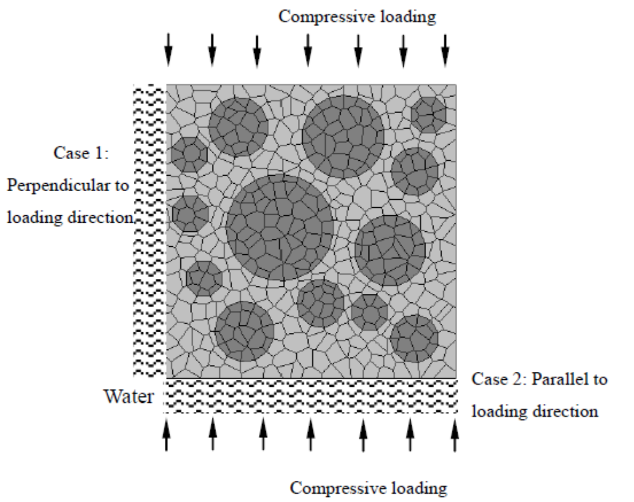


Fig. 4 Geometry of the meshed concrete specimen and analysis conditions under compression

3. NUMERICAL RESULTS AND COMPARISON WITH EXPERIMENTS

3.1 Numerical Models

In this study target concrete is modeled discretely in meso scale as seen in Fig. 4. Mechanical analysis to simulate internal cracks under stresses is conducted by using Rigid Body Spring Network (RBSN) (Wang, et al. 2008), while moisture transfer analysis to simulate capillary absorption is conducted by Lattice Network Model as shown in Fig. 5 (Wang and Ueda 2011). The stress is applied to the target concrete first and then the water absorption is started. It is assumed that the water diffusivity for capillary absorption depends on stress level and internal crack width like that of chloride ion diffusivity which was presented by Wang and Ueda (2011).

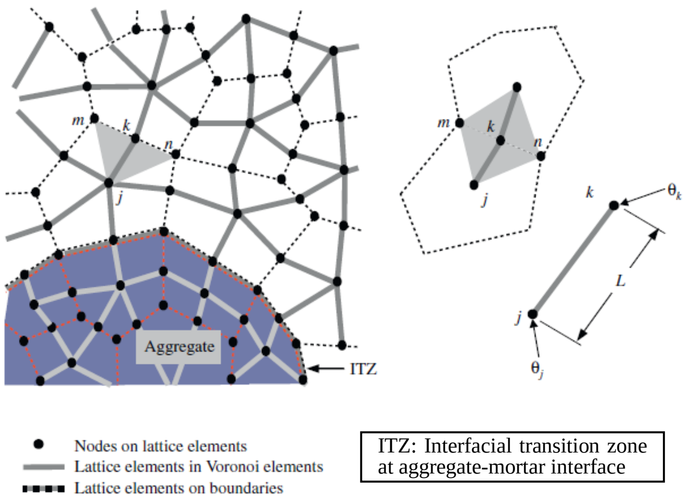


Fig. 5 Lattice Network Model

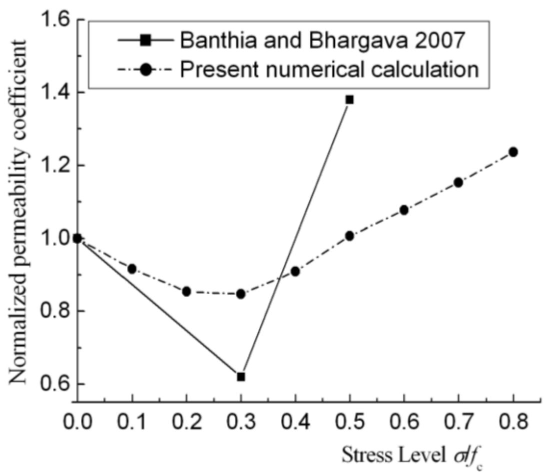


Fig. 6 Effect of compressive stress level on the sorptivity and comparison with test results

3.2 Water Absorption under Compressive Stresses

A series of uniaxial compression analysis by Rigid Body Spring Network (RBSN) are carried out under different stress levels in order to obtain different levels of damage (cracks) in concrete. The thickness and diffusion coefficient of ITZ is set as 20μm and 8.9 times of that of mortar according to Wang et al. (2008). The geometry model of the concrete specimen used in the present study is shown in Fig. 4 with 564 Voronoi elements and 5926 lattice elements. The water penetration is assumed to be either perpendicular or parallel to the loading direction with the side or bottom surface of the specimen exposed to water source. The water absorption time is set as 24 hours and the initial water content is assumed to be zero, implying that concrete is fully dried before exposed to water.

Fig. 6 gives the comparison of the sorptivity between the calculated results under different compressive stress levels and the available test data of permeability rate, in which both the sorptivity and permeability rate were normalized to that of the specimen before loading in order to illustrate the effect of stress level. The direction of water penetration is perpendicular to the stress. Although the calculation results cannot match the test data very well, a consistent tendency can be observed that up to a certain threshold value of stress level, both the permeability and diffusivity decrease with the increase of stress level, but beyond this critical stress level, they begin to increase. This phenomenon has been attributed to the combined effect of pore compression of concrete under lower compressive stress and presence of internal cracking at higher stress levels (Banthia and Bhargava 2007). Fig. 7 compares simulation results of two cases; water absorption direction perpendicular and parallel to the stress. In the former case the water absorption decreases with the increase stress level under small compressive stresses, while in the latter case the water absorption always increases with the increase of stress level. The influence of compressive stress level on water content distribution along the penetration direction after 24 hours is shown in Fig. 8, in which θ denotes the normalized water content, scaled to be zero and one for the initial and saturated volumetric water contents. θ can be written as:

$$\theta = \frac{\Theta - \Theta_i}{\Theta_s - \Theta_i} \tag{2}$$

where Θ is the volumetric water content at any state (i.e. volume of water/bulk volume of concrete); Θ_i and Θ_s are the water contents before contacting with water and at the saturated condition, respectively.

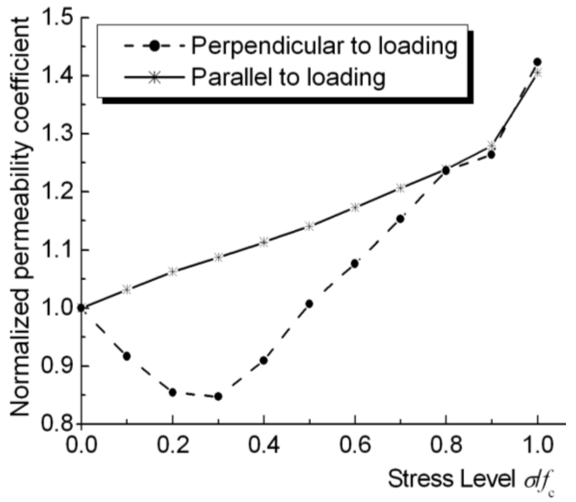


Fig. 7 Results of water penetration direction on the permeability coefficient

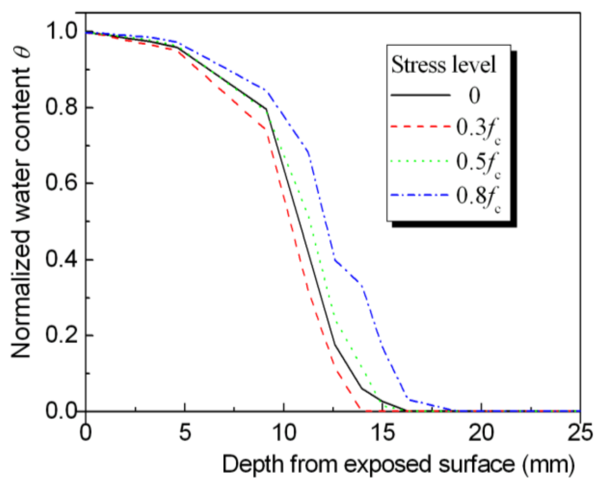


Fig. 8 Water content distribution under different compressive stress levels

3.3 Water Absorption under Tensile Stresses

The analysis conditions for tensile loaded specimens are same as those cases under compression except the exposed surface as shown in Fig. 9, in other words, the left surface is made to represent the water supply boundary because under tensile loading, the majority of cracks propagate perpendicular to the loading direction (Wang et al 2008). The effect of tensile stress level on the water sorptivity is given in Fig. 10. It can be noticed that for concrete samples under tensile loading, the increase of stress level always has a positive influence on the sorptivity. The water content distribution along the penetration direction after 24 hours is presented in Fig. 11 to highlight the effect of tensile stress level.

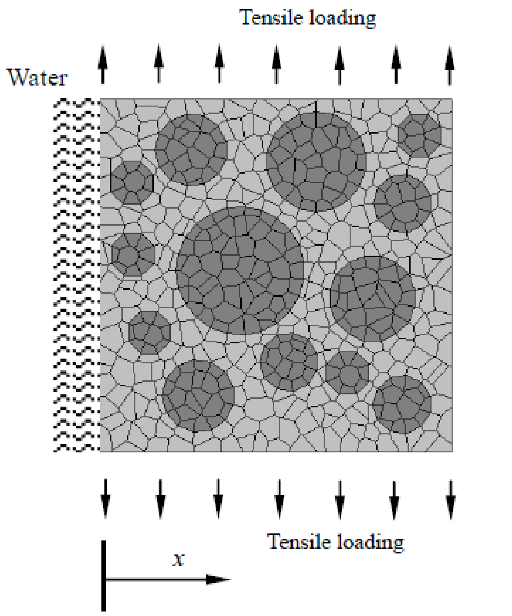


Fig. 9 Analysis conditions of the specimen under tension

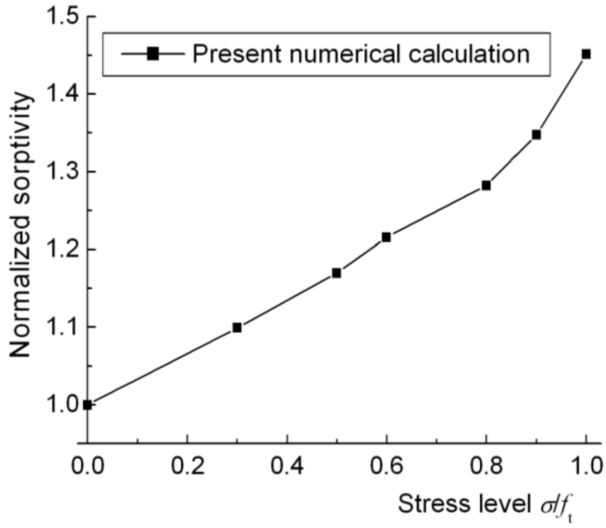


Fig. 10 Effect of compressive stress level on the sorptivity and comparison with test results

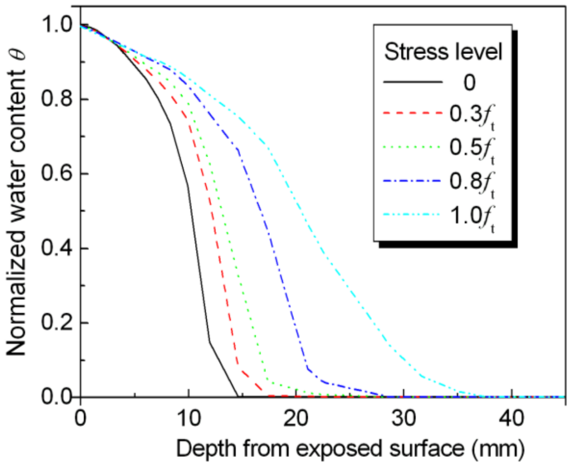
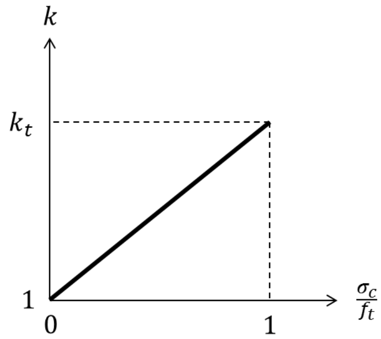
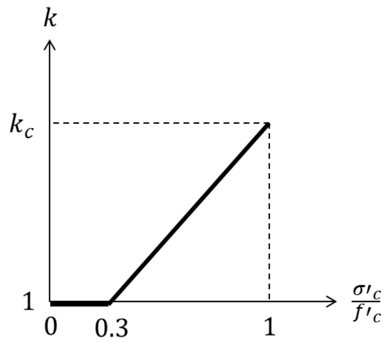


Fig. 11 Water content distribution under different compressive stress levels



(a) Under tensile stress



(b) Under compressive stress

Fig. 12 Magnification factor for diffusivity

4. DURABILITY DESIGN AND PRESTRESSING

4.1 Consideration of Effects of Stress in Uncracked Concrete on Diffusivity

Based on the experimental facts and the numerical simulation results shown in Chapter 3, it is evident that the water diffusivity of uncracked concrete depends on stress level in the concrete. The similar observation was made for chloride ion diffusivity (Wang et al. 2008). Considering those facts, the diffusivity in durability design should be provided as in Eq. (3) rather than simply providing the diffusivity of uncracked concrete:

$$D = kD_0 \quad (3)$$

where D_0 is the diffusivity of concrete without stress, and k is a function of stress level as shown Fig. 12 in which $k_t \approx 1.5$ and $k_c \approx 1.5$.

The present durability design generally uses the diffusivity D_0, meaning that the design diffusivity underestimates the reality.

4.2 Enhancement of Durability by Prestressing

Eq. (3) clearly indicates that prestressed concrete has advantages to non-prestressed concrete. By prestressing tensile stress in concrete members is reduced and even makes it compressive stresses. Under service loadings, stress is limited to around $0.4f'_c$. Consequently the diffusivity in prestressed concrete members would be much less than that in non-prestressed concrete members, meaning that the durability would be enhanced by prestressing.

5. CONCLUDING REMARKS

The diffusivity of uncracked concrete depends on stress level in the concrete. This fact should be considered in durability design, otherwise the design would overestimate the durability. Prestressing which can control stress in concrete would enhance the durability better than the present durability design considers.

REFERENCES

1) Sakoi, Y. and Horiguchi, T., “Loading Effects on Chloride Penetration of Fiber Reinforced Concrete”, Proceedings of the 2nd International *fib* Congress, Naples, Italy, 2006.
2) Banthia, N. and Bhargava, A., “Permeability of Stressed Concrete and Role of Fiber Reinforcement”, ACI Materials Journal, Vol.104, No.1, pp.70-76, 2007.
3) Aldea, C-M., Ghandehari, M., Shah, S, P. and Karr, A., “Estimation of Water Flow through Cracked Concrete under Load”, ACI Materials Journal, Vol.97, No.5, pp.567-575, 2000.
4) Aldea, C-M., Shah, S, P. and Karr, A., “Permeability of Cracked Concrete”, Materials and Structures, Vol.32, No.5, pp.370-376, 1999.
5) Aldea, C-M., Shah, S, P. and Karr, A., “Effect of Cracking on Water and Chloride Permeability of Concrete”, Journal of Materials in Civil Engineering, Vol.11, No.3, pp.181-187, 1999.
6) Wang, K., Jansen, D., Shah, S. P. and Karr, A. “Permeability Study of Cracked Concrete”, Cement and Concrete Research, Vol.27, No.3, pp.381-393, 1997.
7) Zhang P, Wittmann F H, Zhao T J, Lehmann E., “Penetration of Water into Uncracked and Cracked Steel Reinforced Concrete Elements; Visualization by Means of Neutron Radiography”, International Journal of Restoration of Buildings and Monuments, Vol.15, No.1, pp.67-76, 2009.
8) Zhang, P., Wittmann, F. H., Zhao, T. J., Lehmann E. and Jin Z. Q., “Visualization and Quantification of Water Movement in Porous Cement-based Materials by Real Time Thermal Neutron Radiography: Theoretical Analysis and Experimental Study”, Science China Technological Sciences, Vol.53, No.5, pp. 1198-1207, 2010.
9) Ožbolt, J., Balanić, G., Periškić, G. and Kušter, M., “Modelling the Effect of Damage on Transport Processes in Concrete”, Construction and Building Materials, Vol.24, No.9, pp.1638-1648, 2010.
10) Wang L.C. and Ueda T., “Mesoscale Modeling of Water Penetration into Concrete by Capillary Absorption”, Ocean Engineering, Vol.38, No.4, pp.519-528, 2011.
11) Wang L.C., Soda M. and Ueda T., “Simulation of Chloride Diffusivity for Cracked Concrete based on RBSM and Truss Network Model”, Journal of Advanced Concrete Research, Vol.6, No.1, pp.143-155, 2008.