A TWO-PHASE MODEL FOR WATER ABSORPTION OF CRACKED ECC

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1. INTRODUCTION

For concrete structures, cracks are more accessible to water and harmful agents than matrix, causing the accelerated deterioration. Hence, it is necessary to take into account the influence of cracks on the durability. In this paper, based on an existing water transport model for cement matrix, the authors propose a two-phase model which can treat water transport processes of cement matrix with cracks. Furthermore, to verify its applicability, this model is used to simulate water absorption process of Engineered Cementitious Composites (ECC) with multi-cracks.

2. THE EXISTING WATER TRANSPORT MODEL FOR CEMENT MATRIX

In Concrete Laboratory, the University of Tokyo, a multi-scale computational system called DuCOM has been developed to simulate life-span performance of concrete materials and structures (Maekawa et al. 2008). As a basis, hydration, pore-structure formation, as well as water equilibrium and transport in cement matrix are coupled synthetically. For water transport, according to mass conservation, it is described by the following equation

$$\rho\left(\sum \phi_i \frac{\partial S_i}{\partial \mathbf{P}}\right)\frac{\partial P}{\partial t} - \mathrm{div}(K_{tr}\nabla P) + \rho \sum S_i \frac{\partial \phi_i}{\partial t} - W_p \frac{\partial \beta_{chem}}{\partial t} = 0 \tag{1}$$

where, t is time. i represents capillary, gel or interlayer pores in cement matrix, respectively. ϕ_i is their porosity and S_i is pore saturation. ρ is water density. P is water pressure and ∇P represents its gradient. K_{tr} is water conductivity relevant to porosity and size distribution. β_{chem} is chemically bound water ratio and W_p is cement weight per unit volume.

Due to water surface tension, meniscus is generated in the liquid-vapor interface in micropores, and negative water pressure P occurs in the liquid water. According to thermodynamic equilibrium, under an arbitrary relative humidity (RH) h, the pore radius r_c where liquid-vapor interface is present is calculated as follows

$$\ln h = -\frac{2\gamma M}{RT\rho}\cdot\frac{1}{r_c} \tag{2}$$

where, γ is water surface tension, R is gas constant, T is absolute temperature, and M is water molecular mass. Therefore, water status in micropores can be described as Fig.1 shows. It is assumed that pores smaller than r_c are totally filled by water. Pores larger than r_c are partially filled by ink-bottle water and physically absorbed water. The overall water volume is calculated by summing those three portions.

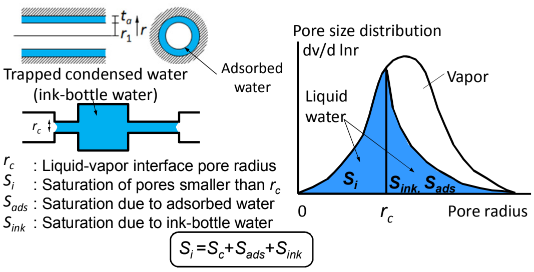

Fig. 1 Water status in pore structure

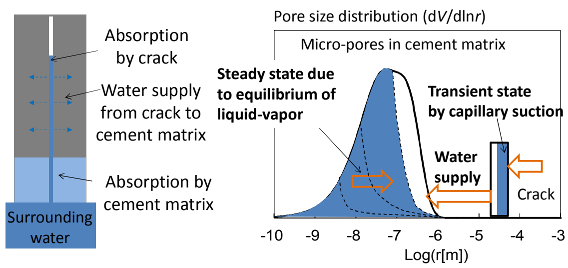

Fig. 2 Water absorption in cracked concrete

3. TWO-PHASE ABSORPTION MODEL

The existing model deals with water transport in cement matrix. When cracks occur, water transport is drastically accelerated, which is caused by the well-known capillary suction. Crack can be regarded as a capillary tube, and by surface tension water ingresses inside at a comparably high speed. Theoretically, if gravity is neglected, the ingression speed increases as the tube radius increases, so larger cracks are more accessible. On the contrary, according to Eq. (2), in the existing model the radius r_c increase as RH increase, and the pores smaller than r_c are fully filled by water. In other word, during wetting process pores are saturated gradually from the small parts. It is thermodynamically a steady state and can be only attained after long time in reality. Since pores in cement matrix are fine, water flow is slow and can be regards as steady state. However, cracks are several orders larger, so the assumption of steady state flow is no longer applicable. Fig. 2 indicates the real process. Water ingresses into cement matrix gradually, but cracks are saturated in a short time. Meanwhile, cement matrix absorbs water from cracks. Therefore, it is difficult to integrate cracks into the existing model, because their dominant mechanisms are different. As a better option, in this study the authors propose a two-phase model which treats cement matrix and cracks separately. The absorption of cement matrix follows the original model, whereas that of cracks is simulated based on capillary suction theory. Cracks are assumed smeared in space field

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and water flow is driven by capillary suction force. Besides, matrix phase absorbs water from cracks. Based on mass conservation, water movements in cement matrix and cracks are described by the following equations, respectively

$$\rho\left(\sum \phi_i \frac{\partial S_i}{\partial \mathbf{P}}\right)\frac{\partial P}{\partial t} - \mathrm{div}(K_{tr}\nabla P) + \rho\sum S_i\frac{\partial \phi_i}{\partial t} - W_p\frac{\partial \beta_{chem}}{\partial t} - \frac{\partial W_{cr}}{\partial t} = 0 \tag{3}$$

$$\rho\phi_{cr}\frac{\partial S_{cr}}{\partial t} - \left(K_{cr}P_{cr}\frac{\partial^2 S_{cr}}{\partial x^2}\right) + \frac{\partial W_{cr}}{\partial t} = 0 \tag{4}$$

where, ϕ_{cr} is the volume fraction of cracks obtained by width and crack number. S_{cr} is the saturation degree of cracks. P_{cr} is capillary suction pressure calculated by water surface tension and crack width. K_{cr} is water conductivity of cracks. W_{cr} represents absorbed water content from crack by cement matrix. Herein, water transport in cement matrix is similar with Eq. (1), but water absorption from crack exists. On the other hand, in cracks water flux is driven by saturation degree gradient of cracks, which is different from water flux driven by pressure gradient in cement matrix.

As suggested by Htut (2012), for a capillary tube with micrometer scale radius, gravity can be neglected and distance of water ingression into capillary tube, l_w, can be expressed as

$$l_w = K_{cm}\sqrt{\frac{\gamma}{2\mu}rt} \tag{5}$$

where, t is the time, γ is water surface tension, μ is the water viscosity and K_{cm} is non-dimensional mean friction factor. Assuming pores in cement matrix as capillary tubes with various radii, according to Eq. (5) it can be deduced that water ingress into coarse pores faster. Fig. 3 shows the image of absorption process from cracks. Coarse pores absorb water and become saturated faster than fines ones. For an oven-dried pore structure, the absorbed water can be obtained by integration of water in all the pores. However, in most cases pore structure is not oven-dried, so the existing water before absorption needs to be subtracted. Since pores smaller than r_c have already been fully saturated, absorption in those pores does not occur any more. On the other hand, pores larger than r_c are only partially filled, so absorption occurs. Because of the space limitation, when pores at an arbitrary radius r are saturated, absorption at this radius stagnates. By integrating absorbed water with all the radii, the total absorbed water is obtained as

$$W_{cr} = \int_{r_c}^{\infty} \mathrm{d}W_{cr} = \int_{r_c}^{\infty} \min(\rho\pi r^2\alpha \cdot \mathrm{d}l_w, dW_{cr}') \tag{6}$$

where, α is effective absorption coefficient relevant to saturation degree of cracks. dW_{cr}' represents the available volume for absorption in arbitrary radius r, which is calculated by subtracting original ink-bottle and physically absorbed water volumes. W_{cr} is differentiated by time and provided to Eqs. (3) and (4) as water exchange of the two phases.

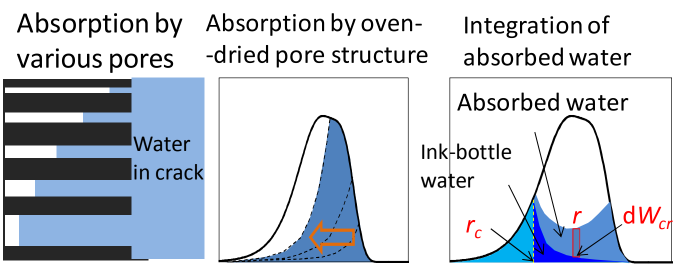

Fig. 3 Water absorption from crack to matrix

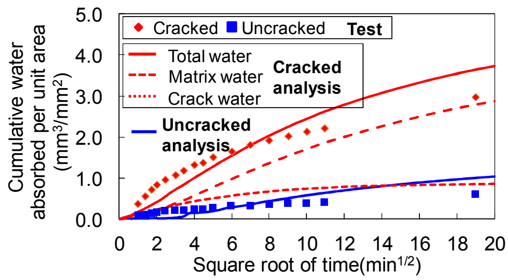

Fig. 4 Simulation of water absorption

With the two-phase model, water absorption of cracked cementitious materials can be simulated. Herein absorption test of ECC conducted by Sahmaran et al. (2009) is adopted for the verification. ECC is a family of fiber reinforced cementitious composites in which multi-cracks with tens of micrometers width occur under tensile load. As Fig. 4 shows, cracks accelerate absorption rate and increase absorbed water greatly, which is well simulated by the proposed model. The acceleration is derived from not only cracks but also water supply from cracks to cement matrix.

4. CONCLUSION

To simulate water absorption of cementitious materials with cracks, a two-phase model which treats cement matrix and cracks separately is proposed. Cracks are assumed smeared, and water transport is described by capillary suction pressure and saturation degree gradient. Water transport in cement matrix is simulated by an existing multi-scale model. Besides, cracks are regarded to supply water to cement matrix continuously. Finally, the proposed model is verified by test of cracked ECC, and the absorption process can be well simulated.

REFERENCES

Htut, T. T.: Numerical Simulation of Long-term Cyclic Drying-wetting Behavior of Concrete under Natural Environmental Action, PhD thesis, Nagaoka University of Technology, 2012.

Maekawa, K., Ishida, T. and Kishi, T.: Multi-scale Modeling of Structural Concrete, Taylor & Francis, 2008.

Sahmaran, M. and Li, V. C.: Influence of Microcracking on Water Absorption and Sorptivity of ECC, Materials and Structures, 42-5, 2009, pp. 593-603.