- Technical Paper -

SIMULATION ON WATER ABSORPTION BEHAVIOR OF ECC MATERIAL WITH DIFFERENT CRACK DENSITY AND DISTRIBUTION

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ABSTRACT

In this study, using a two-phase absorption model, water absorption behavior of ECC with different crack density and distribution are simulated. It is found that higher crack density causes faster absorption and larger absorbed water amount. This is because that cracks become convenient channels for water ingression into cement matrix. Besides, for ECC with severe cracking, cracks are not uniformly distributed but localized in some areas, which causes different water distribution in the absorption. In the analysis, such a process can be reasonably simulated by two dimensional analysis.

Keywords: Water absorption, ECC, crack density, crack distribution, multi-scale modeling

1. INTRODUCTION

Nowadays in Japan Engineered Cementitious Composites (ECC) materials is being widely used in cement and concrete industries. ECC is a family of cementitious composites reinforced by high modulus and strength polymer fibers [1, 2]. It is also called Strain Hardening Cement-based Composites (SHCC). Unlike conventional cementitious materials, when tensile stress surpasses tensile strength of cement matrix, ECC shows very high tensile ductility. Multiple micro-cracks with tens of micrometers width are generated, and an ultimate strain up to several percentages can be achieved, which is several hundred times of that of conventional cementitious materials. Furthermore, self-healing of ECC has been paid attentions [3, 4]. Self-healing is the phenomenon that chemical products precipitate in the multi-cracks and heal ECC without human interventions. It can be attributed to re-hydration of cementitious grains, as well as calcium ion leaching into cracks and carbonation. The self-healing ability of ECC is promising to increase its durability and decrease maintenance cost greatly. On the other hand, the premise of self-healing is the water absorption, providing an aquatic environment for chemical reactions in cracks. It has been found that the water absorption process of cracked ECC is greatly accelerated than that of uncracked ECC [5, 6]. This is because in the case of immersion the so-called capillary suction becomes drastic. Water can be absorbed and fill in cracks in short time. Therefore, in order to evaluate the self-healing effect of ECC, it is necessary to first simulate the accelerated water absorption.

With the purpose of evaluating life-span performance of cementitious materials and structures, a multi-scale computational system called DuCOM has been developed in Concrete Laboratory, the University of Tokyo [7]. Hydration, pore-structure formation, as well as water equilibrium and transport in cement matrix are coupled and simulated to attain water status in micropores of cement matrix under various ambient conditions. Based on this system, the authors have proposed a two-phase absorption model to simulate water absorption behaviour of cracked ECC [8]. In this model, cement matrix and cracks are treated separately. 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 pore pressure gradient and pore-structures. Besides, cracks are regarded as reservoirs and to supply water to cement matrix continuously. This two-phase model has been roughly verified using absorption test of cracked ECC. The fact that water absorption is greatly accelerated due to the existence of cracks can be reproduced. On the other hand, crack status, such as crack density and distribution, strongly influence water absorption rate, but in the verification they have not been fully considered and studied. Therefore, in this paper, for ECC with different crack density and distribution, their water absorption behaviors are studied and discussed using the two-phase model. Before that, the two-phase model is briefly introduced.

2. THE TWO PHASE ABSORPTION MODEL [8]

In the two-phase model (Fig. 1), since the flows in cracks and cement matrix are dominated by different mechanisms and their rates are quite different, cracked ECC is separated into cement matrix phase and multi-cracks phase which overlap in the space field but have independent flows. Water flow in cement matrix follows the transport theory of porous media. Multi-cracks are assumed to be smeared in space field. Crack space is abstracted as equivalent volume fraction in the REV. Water movement is treated as continuous flow along multi-cracks direction. Furthermore, water ingression from multi-cracks to cement matrix is

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treated as the exchange between the two phases. Using mass conservation, in the universal coordinates water flows in cement matrix phase and crack phase are described respectively as

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

$$\rho\phi_{cr}\frac{\partial S_{cr}}{\partial t} - \mathrm{div}(\mathbf{q}_{cr}) + \frac{\partial W_{cr}}{\partial t} = 0 \quad (2)$$

where, t is time (s). i represents capillary, gel or interlayer pores in cement matrix, and ϕ_i is porosity (m^3/m^3). ρ is water density (kg/m^3). S_i is pore saturation degree. P is water pressure in micropores (Pa) and ∇P represents its gradient. K_{tr} is water conductivity in cement matrix which is relevant to porosity and pore size distribution ($kg\cdot Pa^{-1}\cdot m^{-1}\cdot s^{-1}$). β_{chem} is chemically bound water ratio (kg/kg) and W_p is cement weight per unit volume (kg/m^3). W_{cr} is water exchange from multi-cracks to cement matrix (kg/m^3). ϕ_{cr} is multi-cracks volume fraction (m^3/m^3) and S_{cr} is its saturation degree. $\mathbf{q}_{cr}$ denotes flux vector in multi-cracks in the universal coordinates ($kg/m^2\cdot s^{-1}$). Eq. 1 is for cement matrix phase, and the partial differential of W_{cr} with respect to time is set as source term. Eq. 2 is for multi-cracks phase. The first and second terms represent water retaining capacity and flux terms in cracks, respectively. The partial differential of W_{cr} with respect to time is set as sink term.

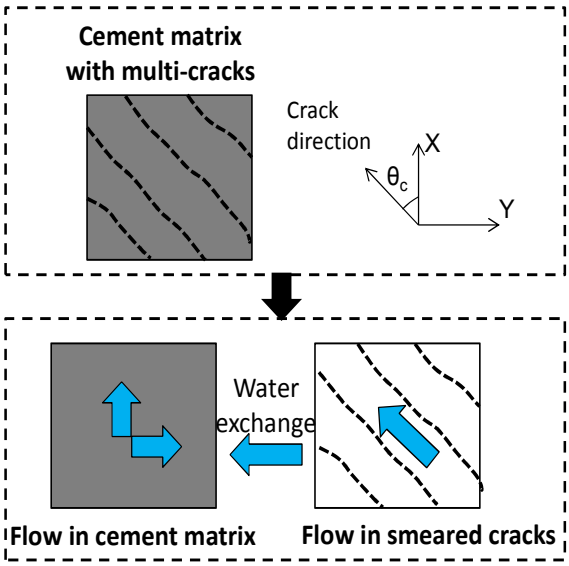


Fig. 1 Scheme of the two-phase model

As a simplest case, in Fig. 1 assume that the angle between multi-cracks and X-axis, denoted as θ_c, equals zero. Therefore, flux vector $\mathbf{q}_{cr}$ is long X-axis, and Eq. 2 can be simply written as

$$\rho\phi_{cr}\frac{\partial S_{cr}}{\partial t} - \left(K_{cr}P_{cr}\frac{\partial^2 S_{cr}}{\partial x^2}\right) + \frac{\partial W_{cr}}{\partial t} = 0 \quad (3)$$

where, P_{cr} is capillary suction pressure (Pa), and K_{cr} is water conductivity in crack phase ($kg\cdot Pa^{-1}\cdot m^{-1}\cdot s^{-1}$). In the model, water flow in cracks is assumed to obey Hagen-Poiseuille equation, so they can be obtained using the following equations

$$P_{cr} = \frac{2\gamma}{w_{cr}} \quad (4)$$

$$K_{cr} = \frac{K_{cr\_0}{w_{cr}}^2}{8\mu} \quad (5)$$

where, γ is water surface tension (N/m). w_{cr} is average crack width (m). μ is the water viscosity (Pa· s). K_{cr_0} is intrinsic conductivity coefficient of multi-cracks (kg/m^3).

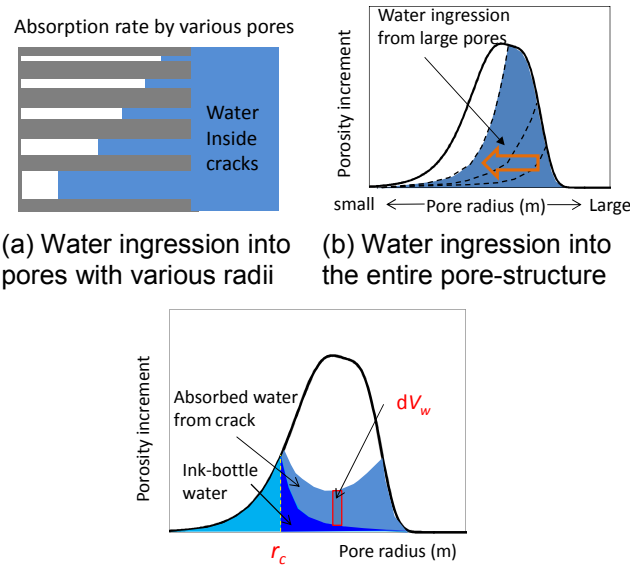
For a capillary tube with micrometer scale radius r, gravity can be neglected and distance of water ingression into the tube (m), l_w, can be expressed as

$$l_w = K_{cm}\sqrt{\frac{\gamma}{2\mu}rt} \quad (6)$$

where, t is the time (s), γ is water surface tension (N/m), μ is the water viscosity (Pa·s) and K_{cm} is non-dimensional mean friction factor. Based on Eq. 6, it can be deduced that water ingresses into large tubes faster than small tubes. Fig. 2 shows the image of ingression process from cracks. If we assume pores in cement matrix as capillary tubes with various radii, according to Eq. 6 water ingresses from cracks into coarse pores faster than fine pores (Fig. 2 (a)). Then, describing the entire pore distribution as a continuous function of pore radius, it is easy to imagine that water absorption first occurs in coarse pores and gradually spread to the fine portions (Fig. 2 (b)). For an oven-dried pore structure, the absorbed water can be obtained by integration of water in all the pores. However, in most cases, before absorption pore structure is not oven-dried, so existing water in cement matrix phase before absorption needs to be excluded. The calculation method is shown in Fig. 2 (c). Since pores smaller than the critical radius (r_c) have already been fully filled by water, water ingression in those pores does not occur any more. On the other hand, pores larger than r_c are partially filled, so ingression 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 water exchange from crack to cement matrix, i.e. W_{cr} in Eqs. 1 and 2, is obtained as

$$W_{cr} = \int_{r_c}^{\infty} \mathrm{d}W_{cr} = \int_{r_c}^{\infty} \min\left(\frac{\pi\alpha T_{cr}K_{cm}}{2}\sqrt{\frac{\gamma t}{2\mu}}r^{3/2}\mathrm{d}r, \mathrm{d}W'_{cr}\right) \quad (7)$$

where, dW_{cr}' represents the available volume for absorption in arbitrary radius r (m^3), α is the factor related to saturation degree of multi-cracks, T_{cr} is factor related to crack density. Crack density is defined as crack number in a unit volume of cement matrix. If the cement matrix contains more cracks, ingression rate from cracks increases because interfacial surface area between cracks and cement matrix increases.



(a) Water ingression into pores with various radii

(b) Water ingression into the entire pore-structure

(c) Water ingression calculation considering the existing water

Fig. 2 Scheme of water ingression from cracks to cement matrix in the two-phase model

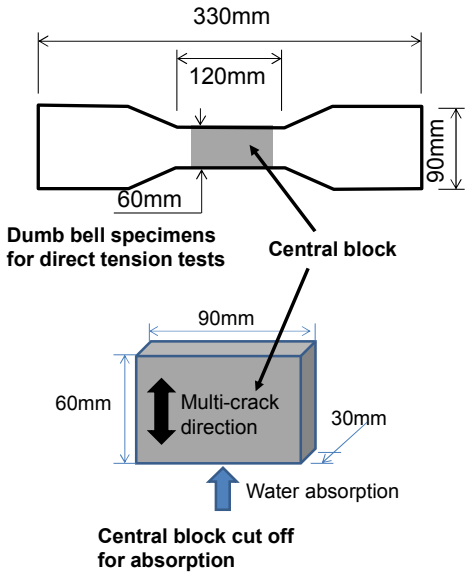


Fig. 3 Specimen shape and dimension [6]

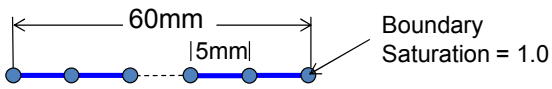


Fig. 4 Meshing of one dimensional analysis

3. WATER ABSOPRTION ANALYSIS

3.1 Details of Absorption Test

In this study, the absorption test of cracked ECC carried out by Wittmann et al. [6] is adopted as the verification. In the test, the water-to-binder ratio of all the specimens is 0.41. The replacement ratios of fly ash and silica fume are 29% and 2% by mass, respectively. 2.0% of PVA fibers were added. First, dumb-bell shaped specimens were cast. After demolded at 1 day, those specimens were moisture cured (RH >95%, 20°C) until the age of 14 days. Then initial strains of 0.0, 0.5, 1.0, and 2.0% were imposed by direct tension test to induce initial multi-cracks, respectively. After that, the tensile loads were removed, and the central part of the specimens, which is block of 90 × 60 × 30 mm, were cut off. The numbers of cracks in the blocks were counted and their widths were measured. Crack numbers and average crack widths were given (Table 1). It can be found that the average crack width almost remains constant, while crack number increases with high imposed strain, which implies crack density increases. Those blocks were dried at 50°C to equilibrium, and then absorption test was conduct by submerging the surface of 90 × 30 mm into water with the depth of only 3 mm above the bottom, to avoid water head pressure. Absorbed water weight was measured. The dumb-bell specimens and blocks are shown in Fig. 3.

Table 1 Mix proportion of ECC [6]

Imposed Strain (%)	Crack number	Average crack width (μm)	Multi-cracks volume fraction
0.5	12	47.7	0.0064
1.0	22	49.9	0.0120
2.0	36	48.7	0.0195

3.2 One Dimensional Analysis for ECC with Different Crack Density

Ideally multi-cracks induced using direct tensile load are vertical to the load direction. Herein, those multi-cracks are assumed to penetrate the thickness (30 mm), and vertical to the absorption surface (90 × 30 mm) and distribute in the plane of 90 × 60 mm uniformly. Hence, one-dimensional analysis in the absorption direction (60 mm) is carried out (Fig. 4). The mix proportion of ECC and ambient conditions are configured completely the same with the test. The saturation degree of the nodes on the boundary which contact water is set as 1.0. Multi-cracks volume fraction in Eq. 2 is calculated by multiplying crack number and average crack width in Table 1, and then divided by water-contacting length (90mm). Those values are assigned to all of elements as necessary material properties. In the uncracked case (0.0% strain), only cement matrix phase exist in the model, so just Eq. 1 is solved and the water exchange term W_{cr} becomes zero.

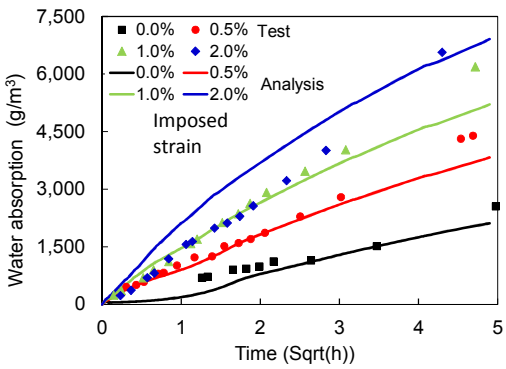
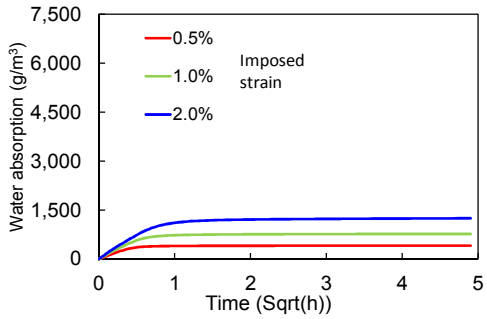
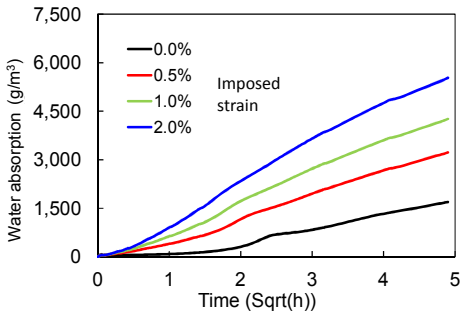


Fig. 5 Overall water absorption analysis



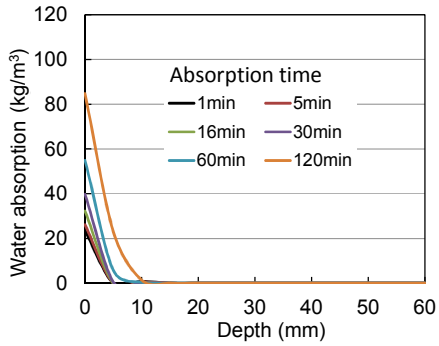
(a) By crack phase



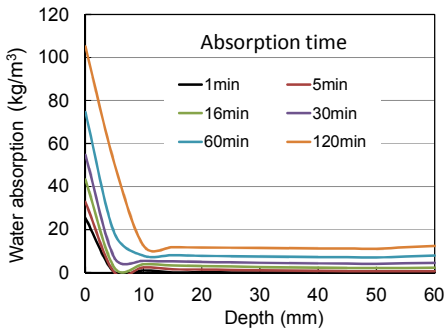
(b) By cement matrix phase

Fig. 6 Analysis of water absorption by crack phase and cement matrix phase

The analytical results of overall water absorption are compared with tests (Fig. 5). The vertical axis represents absorbed water weight per unit volume of ECC, and the horizontal axis is the square root of time (hour). For cracked cases (strain>0.0%), water absorbed by cement matrix and multi-cracks are summed as the overall weight. First of all, in the uncracked case (0.0% strain), the absorption rate in the test is relatively low, and it can be traced using the model for cement matrix phase. For cracked cases, the test shows that as the imposed strain increases, the absorption rate and water weight increase. This is because that more cracks are induced by larger strain. Generally speaking the above tendency can be effectively simulated by the two-phase model. For high strain case (2.0%), deviation between test and analysis can be observed. This may be due to the localization of cracks at high strain, so the assumption of uniform crack distribution becomes no longer appropriate. In Fig. 6, the analysis results of absorbed water in cement matrix and multi-cracks are shown, respectively. It can be seen that within one hour cracks have already become saturated. One the other hand, the absorbed water in cement matrix increases continuously even after one day, implying that the cement matrix is still unsaturated. By comparing the absolute values of absorbed water in cracks and cement matrix, it can be found that most of absorbed water comes from cement matrix rather than multi-cracks, especially at later stage. Furthermore, for higher imposed strain, cement matrix absorbs water much faster than low strain case. This is due to water ingression from multi-cracks to cement matrix. For higher strain case, because more cracks are induced, water ingression from cracks to cement matrix is much more accelerated. Fig. 7 shows absorbed water in cement matrix phase along the depth. For the uncracked case, water content near surface increases slowly, whereas the interior remains dry and absorption does not occur. On the contrary, for the cracked case (0.5% strain), except for rapid absorption near surface, the interior also absorb water. Obviously cracks become convenient channels for water ingression into cement matrix, which can be reproduced by the two-phase model.



(a) Uncracked case

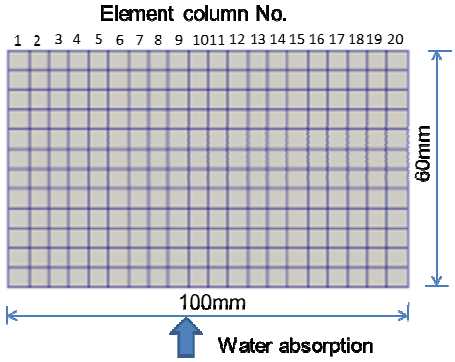


(b) cracked case (0.5% strain)

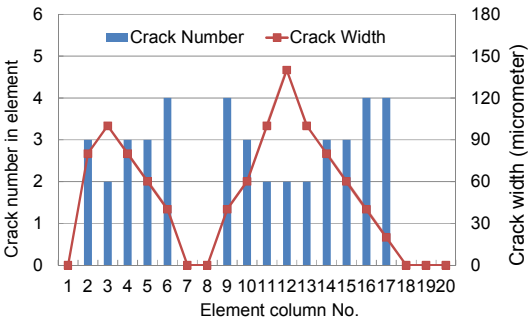
Fig. 7 Analysis of absorbed water amount by cement matrix phase along absorption depth

3.3 Two Dimensional Analysis with Area-localized Crack Distribution

Strictly speaking, the hypothesis that multi-cracks distribute uniformly in the plane is only an ideal state. In reality multi-cracks may become area-localized, especially when large tensile strain is imposed. In the test by Zhang et al. [9], using the same method with the above test from Wittmann et al., 4.0% strain was imposed to a block of 100 × 60 × 30 mm. 42 cracks with average crack width 63.0 μm were found. The maximum crack width is 140 μm. These multi-cracks were observed to be localized in some areas, where water ingression becomes more remarkable. To simulate this process, two-dimensional analysis is necessary and conduct using the two-phase model. As shown in Fig. 8, the elements along horizontal directions (water absorption surface) are divided into 20 columns. For elements in different columns, different average cracks widths and crack numbers are assigned. For example, for all of the elements in the No.6 column, the average cracks width is 40 μm and 4 cracks is set. Still, the overall crack number is 42 and average crack width is 63.0 μm, which is kept consistent with the test.



(a) Meshing



(b) Multi-crack properties in various element column

Fig. 8 Two-dimensional meshing and crack properties for elements in different columns

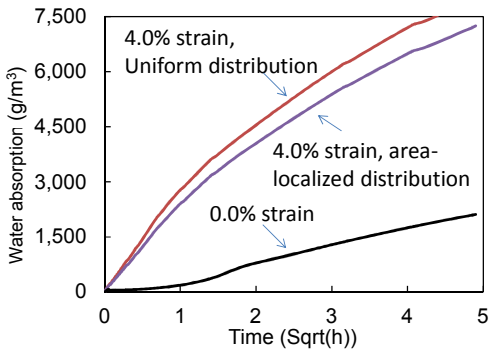


Fig. 9 Analysis of uniform and area-localized crack distributions

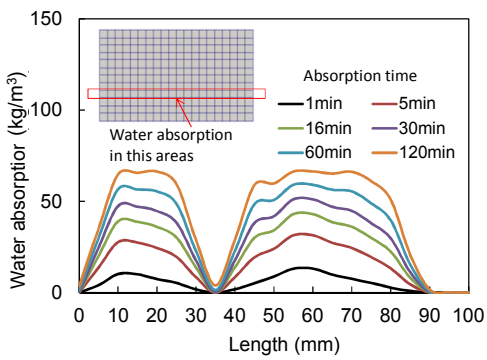


Fig. 10 Water absorption along the length direction

The analytical results of area-localized distribution is shown in Fig. 9 and compared with the uniform distribution using one-dimension analysis. It can be found that absorbed weight of the area-localized distribution is lower than that of uniform distribution. This is because that some areas are still intact, where the water ingression is slow. The above comparison indicates that multi-cracks distribution is also an important factor, especially for high imposed strain and severe cracking case. Back to Fig. 5, it may be one reason for the deviation of analysis from test for 2.0% strain. More studies about multi-cracks distribution and its influence on absorption should be carried out in the future.

Furthermore, in Fig. 10 analysis of absorbed water along length direction (the direction of 100 mm) is shown. Obviously for areas with severe cracking, water ingression becomes more remarkable, which is consistent with the test results using neutron radiography [9]. Finally, water weight contour in cracks is shown in Fig. 11. Water propagation in the areas with multi-cracks can be highlighted, which appears consistent with the observation in the test (Fig. 12). Therefore, the area-localized distribution analysis can reflect the reality more reasonably than uniform distribution.

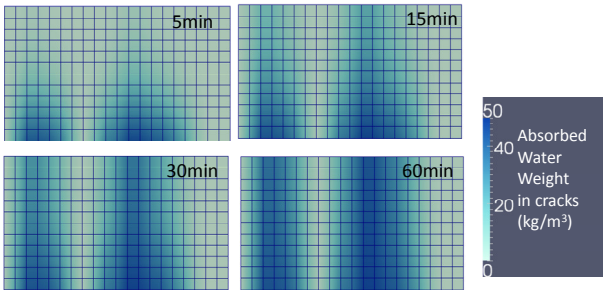


Fig. 11 Water contours in cracks using area-localized distribution analysis

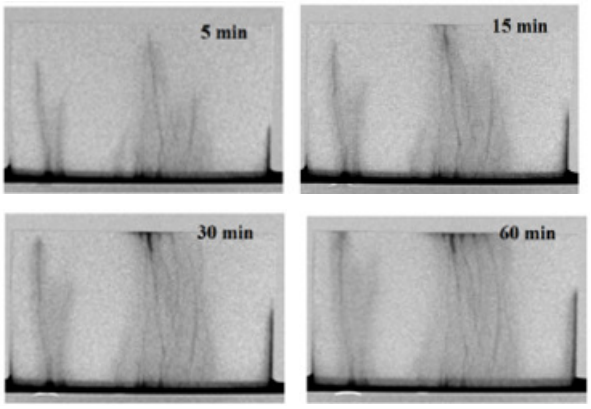


Fig. 12 Observation of water propagation in cracked ECC [9]

4. CONCLUSIONS

Using the two phase absorption model, water absorption behaviors of ECC with different crack density and distribution are studied and compared with test results. Conclusions can be obtained as follows

(1) Water absorption rate and absorbed water amount increases as crack density in ECC increases.

This can be partly attributed to the increased crack space volume. Furthermore, higher crack density implies more convenient channels for water ingression from cracks to cement matrix, which seems a more important reason for the accelerated absorption. Using the two phase model, such an accelerated process can be well reproduced.

(2) For ECC with relatively severe cracking, cracks are not uniformly distributed but localized in some areas. Such a difference in crack distribution may cause different absorption results, especially water distribution in cracked ECC. Therefore, the analysis based on area-localized crack distribution is necessary. Using the two phase model with two dimensional analysis, water absorption of ECC with area-localized cracks are simulated and the result is consistent with the test.

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