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研究課題名（和文）Evaluation system on water transport properties of cracked concrete under environmental conditions

研究課題名（英文）Evaluation system on water transport properties of cracked concrete under environmental conditions

研究代表者
欒　堯（LUAN, Yao）

埼玉大学・理工学研究科・助教

研究者番号：２０７２５２８８

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研究成果の概要（和文）：本研究では，ひび割れを有するモルタルの吸水実験を行い，異なるひび割れ幅での吸水量と吸水速度，および重力，事前乾燥度などの影響について示した．また，微視的な機構に基づいた硬化体・ひび割れの二相系吸水モデルを用い、異なるひび割れ条件での高靱性セメント複合材料ECCの吸水性能を良好に再現することに成功した．さらに，撥水材の混入によって内部撥水性を有するモルタルを試作し，吸水実験を行った．その結果，ひび割れを有する撥水モルタル供試体は，標準供試体・表面塗布供試体と比較すると，吸水率が顕著に減少し，ひび割れ面でも撥水効果を発揮したことが明らかになった．

研究成果の概要（英文）：In this research, water transport properties of cracked cementitious materials were studied. First, water absorption experiment was conducted, with different crack widths, absorption directions and saturation degrees before absorption. Second, a two-phase transport model was established and the water absorption of ECC materials with different crack conditions were analyzed numerically. Since crack becomes convenient channel for water ingression from cracks to cement matrix, the absorption process was greatly accelerated. Such an accelerated process was well reproduced using the model. Then, mortars with internal hydrophobicity were made. Based on absorption experiment, it is confirmed that the specimens with surface coating, when crack occurred, lost their water repellency, whereas the internal hydrophobized specimens remained water repellent state. Therefore, the internal hydrophobized mortar is promising to be used in practice.

研究分野：　工学

キーワード：　コンクリート　ひび割れ　水分移動　二相系モデル　撥水材

１．研究開始当初の背景

Physical and chemical deterioration of reinforced concrete structures is often closely related to the ingress of water. For instance, deleterious substances such as chloride and sulfate ions diffuse into concrete with water, causing corrosion of steel bars and sulfate erosion, respectively. Water itself, as an agent, can also cause chemical or physical attack to concrete. For example, in the case of alkali silica reaction, the gel products swell when absorbing water, and cause expansion pressure to lead to map cracking. In freezing and thawing process, water is directly involved to cause internal stress arising from the expansion when it is freezed.

Furthermore, for concrete structures, cracks are more accessible to water and harmful agents than matrix, causing the accelerated deterioration. Even for high strength concrete with low permeability, when crack occurs, it becomes a convenient channel and the corrosion will be greatly accelerated. During the whole life of structures, it is difficult to completely avoid cracking. Therefore, when we attempt to predict and evaluate the durability, it is unavoidable to study water transport in cracked concrete materials. However, the current studies about water behavior of cracked concrete, including experiment, analysis as well as the prevention method for water ingress, are still insufficient.

２．研究の目的

(1) To clarify water ingress behaviors of cracked concrete by experimental study. It is expected that the relationship between water transport and crack patterns can be elucidated.

(2) To establish an analytical model which couples water transport in crack and cement matrix. It is expected that in the analysis, water content in cracks and overall water weight change of cracked concrete can be simulated.

(3) To develop a type of internal hydrophobic cementitious material. It is expected that even if cracked occurs, the material still holds lower water ingress than traditional cementitious material, due to its bulk hydrophobicity.

３．研究の方法

(1) Experiment of water absorption

Cylindrical mortar specimens were prepared. Tensile splitting load was applied to the specimens to induce crack. Hard steel wires bent in the ends were preliminarily embedded in the specimens (Fig. 1). Due to the load, a penetrated crack in the center occurred. The crack widths were measured. After demolding, the specimens were sealed and stored until the aimed age. Then, they were dried at RH 60%, and after that, tensile splitting load was applied, and cracks were induced with 0.05~0.3 mm widths. Using epoxy the side and bottom surfaces were sealed and a 1.0 cm deep sink was configured at the upper or bottom surface. One dimension absorption was conduct from the top or bottom, and water in the sink was always kept saturated (Fig. 2). Weight gain was measured during the absorption.

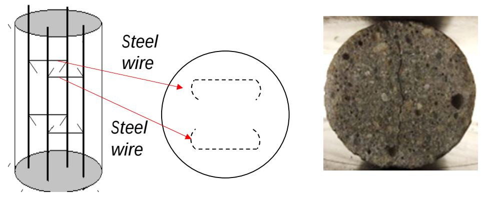


Fig. 1 Crack induction method

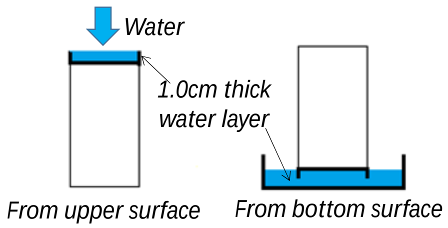


Fig. 2 Water absorption experiment

(2) A two-phase water transport model for numerical analysis of cracked cementitious materials

A two-phase water transport model was established (Fig. 3). The flows in cracks and cement matrix are regarded to be dominated by different mechanisms, and their rates are quite different. The cracked material 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 representative element volume. Water movement is treated as continuous flow along multi-cracks direction. Furthermore, water ingression from multi-cracks to cement matrix is 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.

Fig. 4 shows the image of ingression process from cracks. If we assume pores in cement matrix as capillary tubes with various radii, water ingresses from cracks into coarse pores faster than fine pores (Fig. 4 (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. 4 (b)). By integrating absorbed water with all the radii, the total water exchange from crack to cement matrix can be obtained.

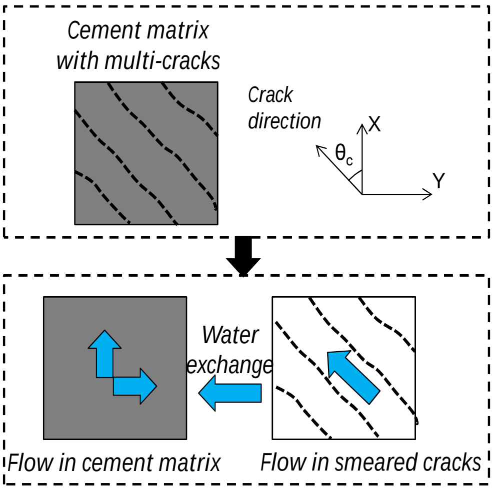
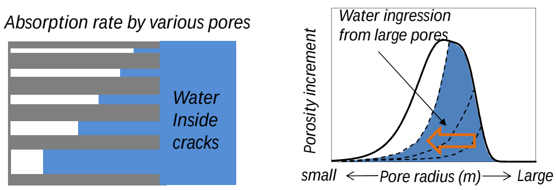


Fig. 3 Scheme of the two-phase model



(a) Water ingression into pores with various radii
(b) Water ingression into the entire pore-structure

Fig. 4 Scheme of water ingression from cracks to cement matrix in the two-phase model

(3) Development of an internal hydrophobic mortar

Two types of silicone-based hydrophobic agents (abbreviated as A and D) were used as admixture, respectively. Two hydrophobizing methods were used as follows.

➢ Direct Mixing method

The hydrophobic agent was directly mixed with water, cement and sand to make mortar.

➢ Sand spraying method

The hydrophobic agent was first sprayed onto the surface of dry sand, and stirred repeatedly to ensure evenness. With this approach, the sand was hydrophobized. Then, the sand was dried for 24 hours, and mixed with cement and water to make mortar.

For the groups of the direct mixing (A-3 and D-3), the addition ratio of the agent to the cement, by weight, was 3.0%. For the groups of sand spraying (A-S and D-S), 50 millilitres of agent was sprayed per kilogram of sand. Specimens were prepared for water absorption, strength, and shrinkage experiment. All of the specimens were cured with sealing until the aimed age. For some of the cylindrical specimens for absorption experiment, crack was induced. Tensile splitting load was applied using the method in Fig. 1.

4．研究成果

(1) Results of experiment of water absorption

Weight grain during absorption was divided by the initial weight of specimens to obtain water absorption ratios. Fig. 5 shows the water absorption ratio, for the absorption from upper surface. It can be found that compared to the uncracked one, water absorption ratios of cracked mortar increase greatly. Obviously crack becomes the shortcut entrance of water. On the other hand, for different crack width, little difference was found between the final water absorption ratios after long time absorption (hundreds of hours). This trend can be also observed in the results of other groups. In addition, if we focus on the early time such as the initial 12 hours, water absorption ratio increases as crack width increases. It can be induced that crack width mainly influences short time absorption rather than that of long time. Furthermore, the influence of gravity can be neglected.

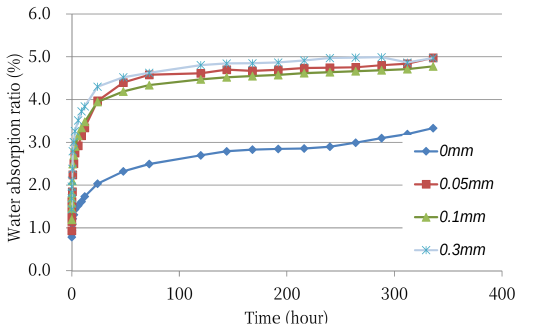


Fig. 5 Water absorption from upper side with various crack widths

(2) Analysis of water absorption of ECC materials using the two-phase model

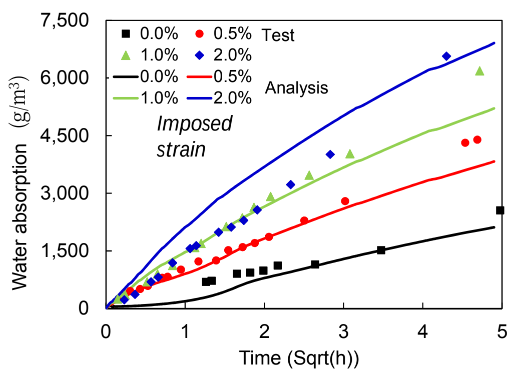


Fig. 6 Overall water absorption analysis

The analytical results of water absorption for ECC materials with different crack conditions (herein represented by imposed strain ratio) are compared with tests (Fig. 6). 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 only 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. This tendency can also be effectively simulated by the two-phase model.

Furthermore, ECC material with more severe imposed strain (4.0%) and area-localized cracks were analyzed, and water weight contour in cracks is shown in Fig. 7. Water propagation in the areas with multi-cracks can be highlighted, which appears consistent with the observation (Fig. 8).

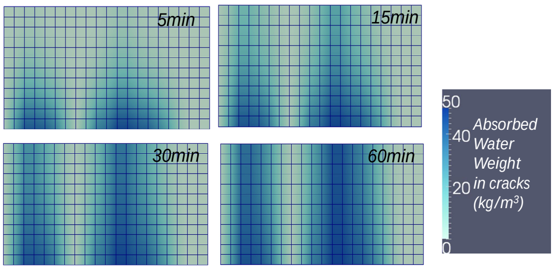


Fig. 7 Water contours in cracks using area-localized distribution analysis

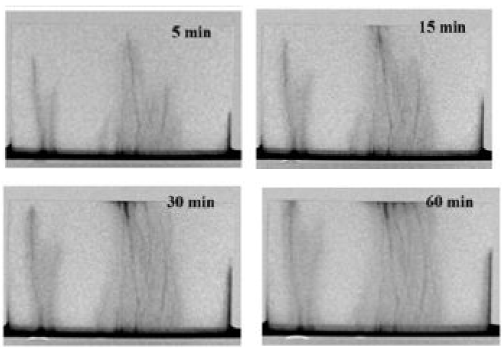


Fig. 8 Observation of water propagation in cracked ECC (Experiment from Zhang et. al 2010, *Observation and quantification of water penetration into strain hardening cement-based composites (SHCC) with multiple cracks by means of neutron radiography*)

(3) Water absorption of the internal hydrophobic cementitious material

Fig. 9 shows the result of the contact angle measurement. According to the results, the average contact angle of the mortar without hydrophobizing treatment, was 3.4˚. For the groups using agent A, the contact angles for the mixing method and the spraying method were 9.5˚ and 31.1˚, respectively. Those values for groups D were much larger, which were 91.1˚ and 98.5˚. Water tended to be spherical shape at the surface of mortar in those cases. Therefore, it can be concluded that silicone agent A had some effect for the hydrophobizing, whereas silicone agent D was much more effective.

Fig. 10 shows the absorption ratios of cylindrical specimens under drying-wetting cycles. The results of uncracked specimens are shown in Fig. 10 (a), whereas those of the cracked ones are shown in Fig. 10 (b). In case of the uncracked condition, except A-coating, for all of other specimens with hydrophobizing treatment, surface coating, direct mixing, or sand spraying, the absorption ratios were lower than that of the reference one (Ref.). Thus, it is concluded that both the surface and internal hydrophobizing treatments were effective when the specimens were sound. On the other hand, in the case of the cracked specimens, the absorption ratios of both the surface coating and the reference ones increased significantly, whereas those of the internal hydrophobized ones were kept low like that of the uncracked ones. The surface coating ones had a slightly higher absorption ratio than the reference one, which may be attributed to the slight difference of the crack width. Undoubtedly, the surface coating ones lost their water repellency when crack occurred, but the internal hydrophobized ones had good water repellency all the same.

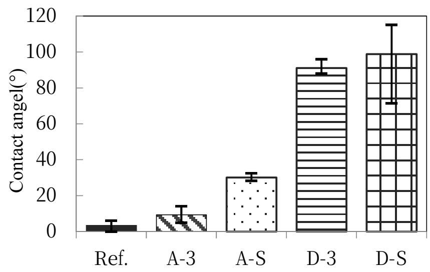


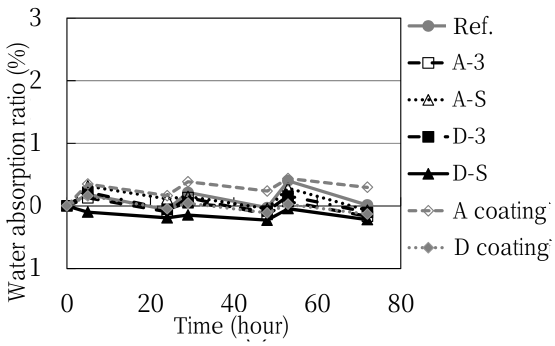
Fig. 9 Result of contact angle

(4) Summary and Conclusion

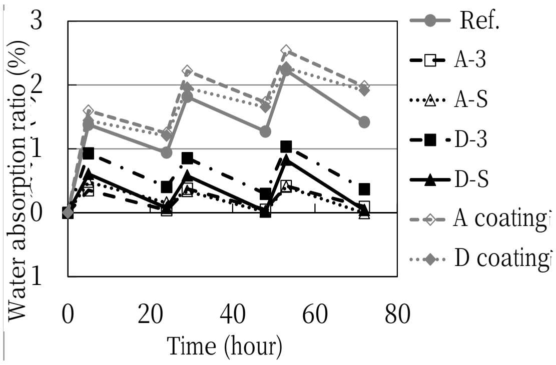
① water absorption of cracked specimens was investigated experimentally. Although crack accelerated water absorption greatly, crack width does not show significant influence on the absorption ratio after long time. However, for the initial hours, larger crack width caused faster water absorption. Furthermore, the influence of gravity can be neglected.

② Water absorption rate and absorbed water amount increases as crack density in ECC increases. 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. 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. The analysis based on area-localized crack distribution was successfully conducted.

③ Internal hydrophobic mortars were made, with adding two different hydrophobic chemical agents. Two manufacturing methods, which were directly mixing and preliminary spraying on sand, were conduct. It is found that the contact angle was increased and water absorption ratio was decreased greatly. It is experimentally confirmed that the specimens with surface coating, when crack occurred, lost their water repellency, whereas the internal hydrophobized specimens remained water repellent state. Therefore, such internal hydrophobized mortar is promising to be used, due to lower water ingress under cracked condition.



(a) Specimens without crack



(b) Specimens with crack

Fig. 10 Results of water absorption ratio under drying-wetting cycles.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計 4 件）

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〔学会発表〕（計 1 件）

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〔図書〕（計 0 件）

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権利者：
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発明者：
権利者：
種類：
番号：
取得年月日：
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〔その他〕
ホームページ等

６．研究組織
(1)研究代表者
欒　尭　(LUAN, Yao)
埼玉大学・理工学研究科・助教
研究者番号：２０７２５２８８

(2)研究分担者
(　　　)

研究者番号：

(3)連携研究者
(　　　)

研究者番号：