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Quick water movement around concrete cracks under unsaturated conditions

Naoko Tsuchiya [a],*, Manabu Kanematsu [b], Takafumi Noguchi [c]

[a] Department of Building Materials and Components, Building Research Institute, 1 Tachihara, Tsukuba, Ibaraki 305-0802, Japan
[b] Faculty of Science and Technology, Tokyo University of Science, 2641 Yamasaki, Noda, Chiba 278-8510, Japan
[c] Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan

HIGHLIGHTS

- From experiment, water movement in a crack decelerates dramatically in minutes.
- From experiment, water movement around a crack is expressed in the quadratic root of time.
- Water content profiles do not show the popularly known one at the early phase.
- Water movements in cracks are similar to water movements into concretes in this study.

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ABSTRACT

The purpose of this research is to detect the water penetration, especially around concrete cracks, under unsaturated conditions at an early time by neutron radiography. The previous known theories of water movement in concrete are verified by the experimental results, both in cracks and around cracks. The results show that water movement in a crack decelerates dramatically in minutes. They also indicate that water movement in some kinds of concrete cracks should be treated in the same way as water absorption into concrete, which described diffusion dominated inflow only after a few minutes.

1. Introduction

Recently, reinforced concrete constructions are required to have good durability with maintenance. It is well known that water affects the durability of reinforced concrete buildings. Therefore, it is important to indicate the state of water and to know water behavior in concrete, and many have researched such things since early times. Concrete is a porous material having a complicated pore structure, and it has a distribution of a pressure, temperature and water concentration internally. Those distributions drive water movement.

If concrete has a crack which brings a deterioration factor into concrete easily, it might have partial deterioration under unsaturated conditions. However, the relationship between cracks and deterioration has not yet been settled. One of the reasons for that is that water movements in concrete under unsaturated conditions are unknown. Almost all past studies on water through concrete cracks have dealt with the water leakage as a steady flow in the saturated conditions. There are only a few experiments about water movement in cracks under unsaturated conditions in previous studies.

Fujioka et al. [1] studied water droplet distribution in concrete cracks as spaces by plates of vinyl chloride and mortar. Kanematsu et al. [2] applied neutron radiography and caught the outline of water behavior in a concrete cracks dynamically by imaging. Images of five minutes after water was applied were obtained. Zhang et al. [3] caught an outline of water penetration into cracked steel reinforced concrete dynamically by imaging used neutron radiography. The images showed that water absorbed into a crack and reinforcing bar quickly at one minute after water was applied and then penetrated via cracks at 30 min. Pease et al. [4] assessed the portion of the crack length contributing to water sorption at 1, 2, 3, 4, 6 and 24 h in the concrete using X-ray absorption. Gardner [5] investigated the capillary flow in discrete cracks in mortar by experimental studies and correcting the number of parameters of existing capillary flow theory such as friction. Water absorption was measured every 0.05 s up to the six second mark. Mainguy et al. studied about demineralization of cementitious materials through water movement in a crack by theory considered

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* Corresponding author. Tel.: +81 29 864 6621.
E-mail addresses: tsuchiya@kenken.go.jp (N. Tsuchiya), manabu@rs.noda.tus.ac.jp (M. Kanematsu), noguchi@bme.arch.t.u-tokyo.ac.jp (T. Noguchi).

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advection and diffusion, from a long-term perspective. The effects of cracks from 0.1 to 1 mm width were analyzed [6]

The purpose of this research is to measure water movement, especially around concrete cracks under unsaturated conditions from several terms of seconds to 1 h, which previous researches have not studied. The previous known theories of water movement in concrete are verified by the experimental results. Water movement both in cracks and around cracks in concrete is evaluated in this research.

2. Methods and materials

2.1. Specimens

The mix proportions are shown in Table 1. Ordinary Portland cement was used in this study. Concrete specimens 100 mm × 100 mm × 20 mm in size were made with a water–cement ratio of 0.65, 0.50 and 0.30, and the relative water content of the concrete were controlled to 0% (0%RWC), 30% (30%RWC) and 60% (60%RWC). Relative water content denotes ratio of quantity of water to full quantity of water in concrete. 100% in relative water content is equal approximately to 0.07 in fractional water content in these specimens. All specimens were submerged in water at 20 ± 2 °C 24 h. After 28 days, 100%RWC specimens were dried at 105 °C to control the relative water content.

Fig. 1 shows the specimens' specifications for water behavior in concrete through cracks. Each specimen was cut out from a beam specimen measuring 100 × 100 × 400 mm. Two patterns of horizontal cracks were examined. One of them was made by cutting so that the crack is a straight line, and the other was bent by a high-rigidity loading machine so that the crack is irregular. Every crack width on the surface is controlled to be 0.05 mm.

These are sealed by aluminum tape with epoxy-bond excepting the water application surface. An aluminum tank to apply water was attached to each specimen using epoxy-bond on one of the edges having the crack end.

2.2. Test method

Tests were performed at the thermal neutron radiography facility called TNRF. This method can capture only liquid water. It is known that it has a linear relationship between the neutron transmissivity and the volume water content of concrete [2]. In this regard, relative water content is expressed in the ratio of neutron tannsmissivity by one per hour after starting test in this research. In other words, it is regarded as a ratio between water content and the one under saturated conditions. The specimen was set as a neutron beam going along the *z* axis direction in Fig. 1, and set at 10 cm from the converter to cut off the scattered neutrons. After measuring the initial intensity by neutron radiography, the aluminum tank was filled with water from the filling port. A series of images were taken every eight seconds serially for 1 h.

2.3. Outline of facility

TNRF as shown in Fig. 2 is installed in a research reactor in the Japan Atomic Energy Agency (JAEA). This facility consists of a fluorescent converter (^{6}LiF/ZnS:Ag), two quartz mirrors, one lens (Nikon Micro-Nikkor 105 mm) and one C-CCD (cooled charge coupled device) camera (C4880:Hamamatsu Photonics), the characteristics of which are shown in Table 2. The neutron flux was 1.2×10^8 (n/cm^2/s).

Neutrons from the reactor are irradiated onto an object, and transmissive neutrons are converted visible light which are imaged by a CCD camera through mirrors.

2.4. Evaluation

Existing capillary flow theory has been applied to water movement in cracks of porous materials as shown in Eq. (1), known as the Washburn equation. Some were improved for concrete cracks by using friction coefficients and so on.

$$l = \sqrt{\frac{d^2}{6\eta} \cdot \Delta P \cdot t} \qquad (1)$$

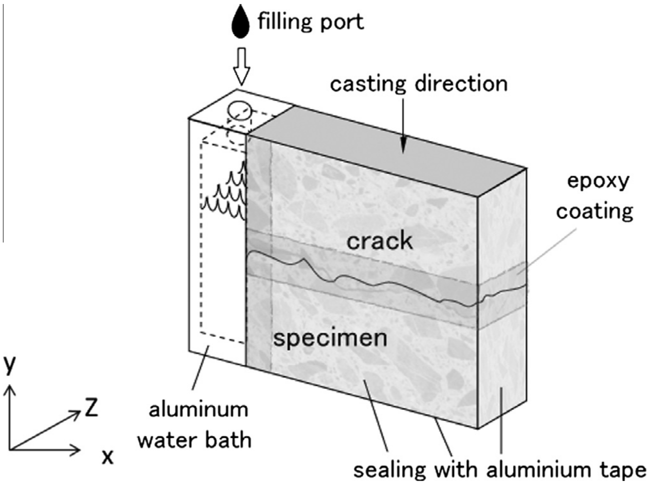

Fig. 1. Schematic illustration of a specimen.

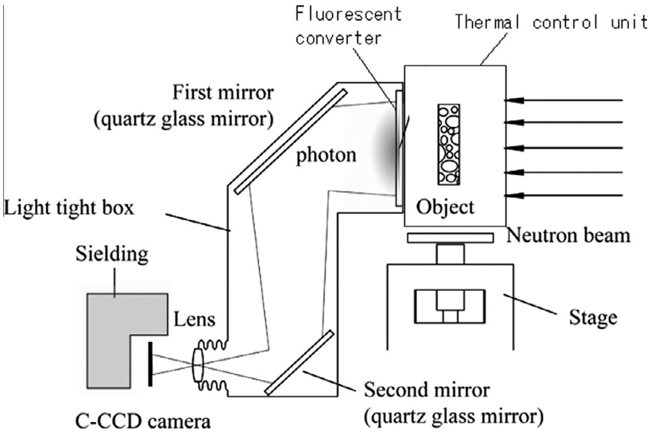

Fig. 2. Schematic illustration of imaging system in TNRF.

Table 2
Facility characteristics of TNRF.

Neutron flux	1.2×10^8 (n/cm^2/s)
Collimation ratio, L/D	Horizontal 176 Vertical 153
Size of image	1008 × 1024 (pixel) (14 bit)
Spatial resolution	100 μm/pixel
Fluorescence neutron converter	^{6}LiF:ZnS(Ag)
Lens	f105 m
Time for one image	2.5 (s) (include data transfer time)

l is Length of water migration (m), *d* is the Width of crack (m), η is viscosity coefficient (Pa s) ΔP is pressure difference (N/m^2) water movement in concrete crack is evaluated by comparing Eq. (1) and the experimental results.

Meanwhile, the prediction model of water movement in porous materials is shown in Eq. (2), known as a nonlinear diffusion equation.

Table 1
Proportion of concrete.

W/C (%)	Maximum size of aggregate (mm)	Sand to aggregate ratio (%)	W (kg)	C (kg)	S (kg)	G (kg)
30	20	43	175	583	665	911
50	20	48	175	350	856	911
65	20	48	185	285	870	925