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Quick water movement around a crack of concrete under unsaturated conditions

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ABSTRACT

It is necessary to identify the deterioration factors of reinforced concretes. It is well known that the water affects the durability of reinforced concrete buildings. But few experiment researches have been made on how the water penetrates through cracks of the concretes under unsaturated conditions. The purpose of this research is to measure 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 evaluated by the experimental results, both in cracks and around cracks. The results show that water movement does not follow such theories. 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 has more than two main phases.

Keywords. Water movement, Crack, Unsaturated condition, Neutron radiography, Concrete

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 (Fujioka et al. 1996) studied water droplet distribution in concrete cracks as spaces by plates of vinyl chloride and mortar. Kanematsu (Kanematsu et al. 2009) 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. P. Zhang (P. Zhang et al. 2010) 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 minutes. Pease (Brad Pease et al. 2009) assessed the portion of the crack length contributing to water sorption at 1, 2, 3, 4, 6 and 24 hours in the concrete using X-ray absorption. Gardner (Gardner, 2012) 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 seconds up to the six second mark.

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

METHOD AND MATERIALS

Specimens. The mix proportions are shown in Table 1. Ordinary Portland cement was used in this study. Concrete specimens 100mm × 100mm × 20mm 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). All specimens were submerged in water at 20±2°C 24 hours. After 28 days, 100%RWC specimens were dried at 105°C to control the relative water content.

Figure 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.

Table 1. Proportion of concrete

W/C	G max	s/a	W	C	S	G
(%)	(mm)	(%)	(kg)	(kg)	(kg)	(kg)
30	20	43	175	583	665	911
50	20	48	175	350	856	911
65	20	48	185	285	870	925

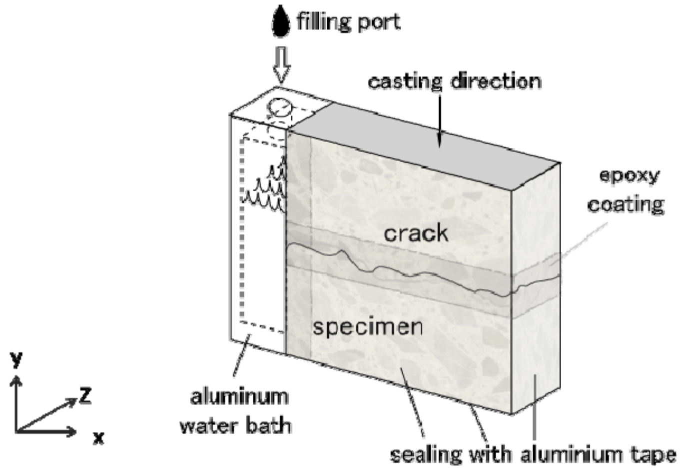

Figure 1. Schematic illustration of a specimen

Test method. Tests were performed at the thermal neutron radiography facility called TNRF. This method can capture not only moisture vapor but liquid water. The specimen was set as a neutron beam going along the z axis direction in Figure 1, and set at 10cm 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 hour.

Outline of facility. TNRF as shown in Figure 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 105mm) 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}/sec).
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.

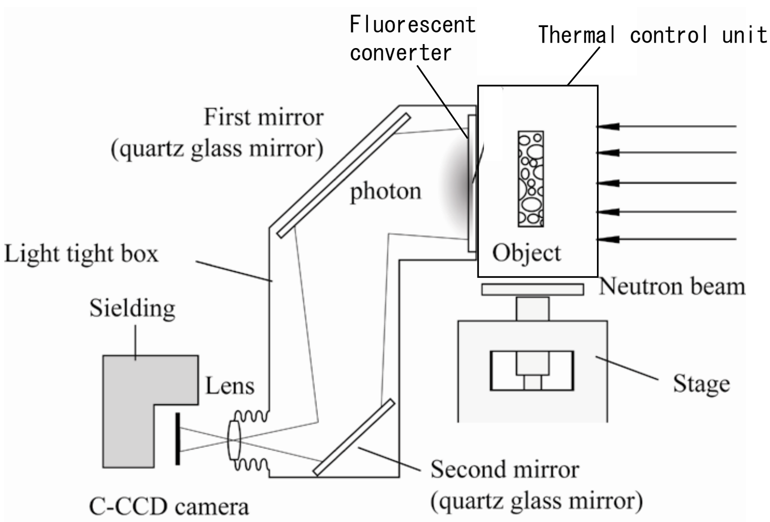

Figure 2. Schematic illustration of imaging system in TNRF

Table 2. Facility characteristics of TNRF

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

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

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

l : Length of water migration (m)
d : Width of crack (m)
η : Viscosity coefficient (m^2/sec)
ΔP : Pressure difference (N/m^2)

Water movement in concrete crack is evaluated by comparing Equation (1) and the experimental results.

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

$$\frac{d\theta}{dt} + \nabla\left(- D\nabla\theta\right) = 0 \tag{2}$$

θ : Relative water content (m^3/m^3)
D : Diffusion coefficient (combined both that of moisture vapor and liquid water) (cm^2/day)

In cases where the diffusion coefficient does not depend on space, it is acquired by applying the profile of water content to the following Equations (3) and (4).

$$D = -\frac{1}{2}\frac{d\lambda}{d\theta}\int \lambda \cdot d\theta \tag{3}$$

$$\lambda = \frac{x}{\sqrt{t}} \tag{4}$$

In addition to evaluation by comparing to Equation (1), experimental results of profiles of relative water content are evaluated. Relationships between λ and the relative water content are also evaluated.

RESULTS ANS DISCUSSION

Shape. Figure 3 shows the TNRF imaging result of a sequence of water movement into concrete though a crack. The result shows that water quickly moved into the crack at 24, 48 and 72 seconds, then moved comparatively slowly and was absorbed into the concrete at 5 and 10 minutes, and was then slowly absorbed into the concrete at 20 and 60 minutes.

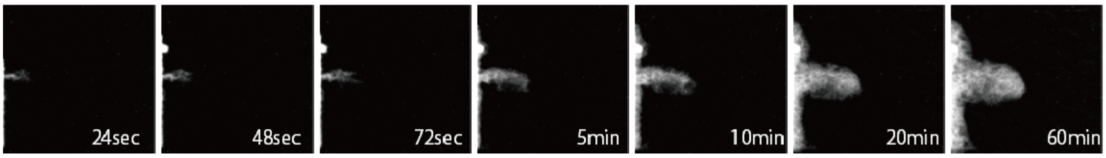

Figure 3. TNRF imaging result of a sequence of water movement into concrete though a crack (C50-30-0.05H)

Water migration length along a crack. Figure 4 shows the shift of water migration length in the crack. Also, it is showed the prediction result by the Washburn equation, in which 0.005 and 0.015 is adopted as $\sqrt{\frac{d^2}{6\eta}\cdot\Delta P}$. Those values do not have a particular meaning but are taken because the results of Equation (1) are relatively close to the experimental results.

From Figure 4, neither experimental result is an exponential approximation as the Washburn equation but show that the migration velocity slows down at once. Therefore fixed $\sqrt{\frac{d^2}{6\eta}\cdot\Delta P}$ is not in correct. Thus, this indicates ΔP takes various values. Especially, there are more than 2 types of depictions of ΔP because the migration velocity changes at once in an obvious way. Pease indicated the correlation between the length of concrete cracks and the length of water movement in the crack (Pease, 2009). Therefore such a rapidly velocity change of water movement in a crack as noted above is discussed below. The air, including moisture vapor which gets jammed by liquid water, is absorbed into a crack to prevent liquid water from going along the crack. However, the jammed moisture vapor becomes diffused into the concrete slowly, so that the liquid water in the crack moves slowly. Although coarse aggregates around the crack and flection could slightly prevent water from moving into a crack, it hard to say that it is a dominant factor of this behavior. The results for cut specimens show almost the same behavior.

From this, it is important for simulations of water movement in concretes cracks to specify what the predominant driving force is. In particular, it should be evaluated as to how predominant factors change, how much is the force, and so on. Or else, the relative water content around a crack in concrete is estimated as less than reality, because it used to be confirmed by comparison between the simulation results and experimental results without any reference to the early phase.

Also, it is indicated from Figure 4 that there is little difference for the specimens prepared. So, the differences of the conditions of relative water content, the water cement ratio, and flection of cracks are minor predominant factors for water movement in concrete cracks on the condition that both the crack width and length are same. Also, Gardner (Gardner et al. 2012) studied absorption in mortar cracks, and indicates that there is little difference for the

results of migration length on any conditions of curing and relative water content. The crack widths studied by her are more than 0.1mm. Meanwhile, Gardner indicates the flection of natural cracks could prevent water from moving in a mortar crack.
This indicates that the conditions in pores such as whether they have water or not and the pore structure of the concrete are not dominant factors for water movement in a crack, but a flection could have an effect, only if the crack width is more than 0.05mm without gravity.

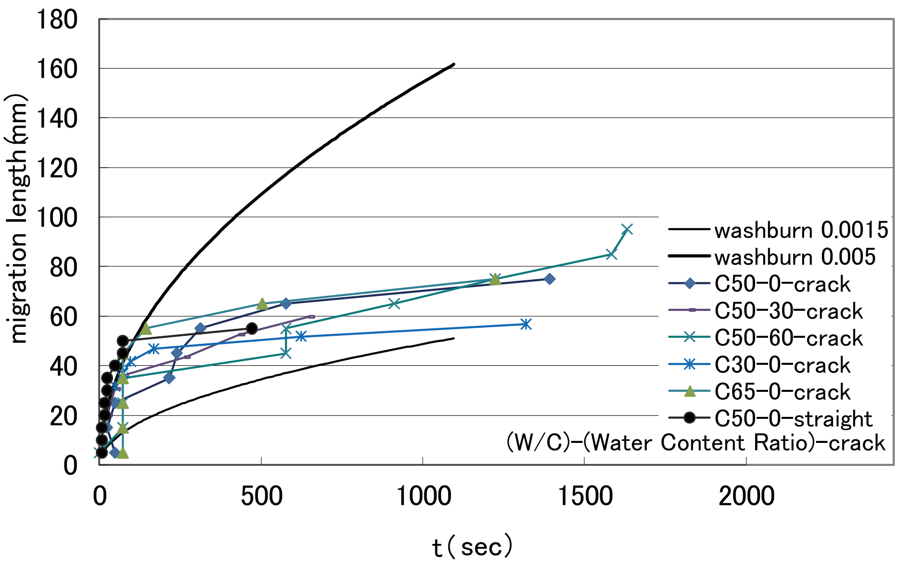

Figure 4. Process of water migration length in a crack

Profiles of relative water content along a crack. Figure 5 shows the profiles of relative water content along the crack of the C50-0 specimen. The method of transformation from the neutron transmissivity to the relative water content of concrete is chiefly applied using the method Kanematsu has (Kanematsu et al. 2009). 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 values used for analysis are an average of each 2mm square on the crack. So the results to some extent contain water behavior in concrete from a crack, and give a rough assessment.
The results show that the length of water movement along the crack increases before the relative water content is full up to 120 seconds, and then, both the length and the relative water content slightly increase. Each profile at 600, 1200, 3000 seconds is similar to Figure 6, which is a schematic illustration of the relative water content profiles, drawn from Akita's study on water absorption in concrete (Akita et al. 1996) .
What is indicated here is that profiles of water in concrete crack after 300 seconds could be a scaling of the profile of the absorbed water into the concrete, in the case of the property of the prepared specimen's crack in this research as the length is 10cm, and the width is 0.05mm.
Therefore it is possible for some kind of concrete cracks to be treated in the same way as water movement in porous materials except in the early phase.

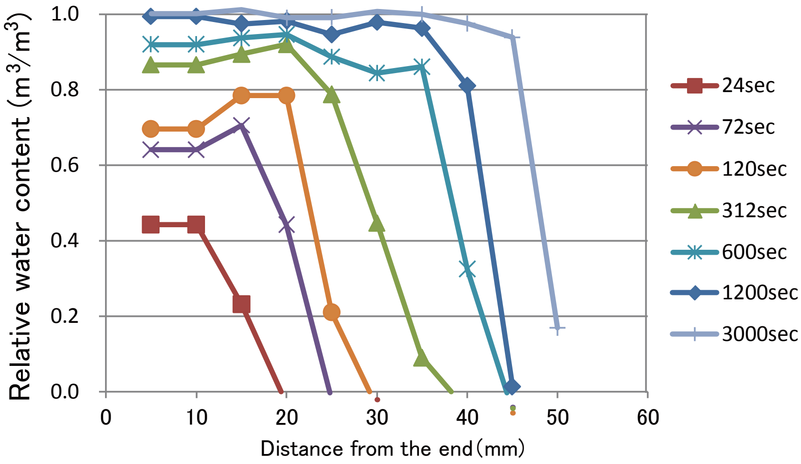

Figure 5. The profiles of relative water content along the crack of the C50-0 specimen

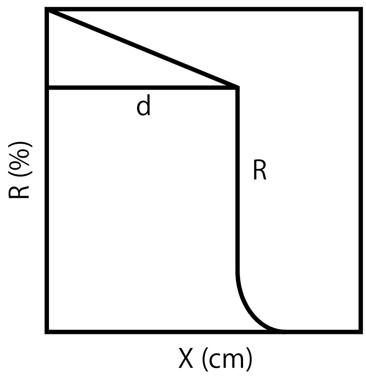

Figure 6. Schematic illustration of relative water content profile in concrete known from past studies

Process of migration length in the direction at right angles to a crack. Water absorption into concrete from a crack was analyzed next. Figure 7 shows the relationship between water migration length in the direction at right angles to the crack and the square root of time. It is taken for analyzing at a point 3 cm distant from the end where the water comes. The time when the water got up to that point corresponds to time 0. The result shows that the relationship is not a linear performance. Some past studies (C. Hall et al. 1995), (Akita et al. 1996), (L. Hanzic et al. 2003), (C. Hall, 2007) indicate that water absorption form the bottom aspect into concrete is as the same as noted above. But, past researches have not studied the terms of early phases such as in this study. So, the cause of non-linear performance of water movement from cracks into concrete is not simply for the sake of movement through a crack. But, it hardly makes mention of other factors, which is to be solved.

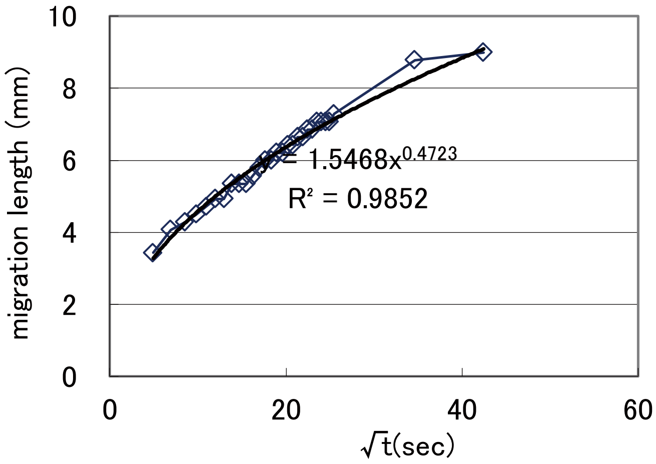

Figure 7. The process of water migration length in the vertical direction of a crack

Profile of relative water content in the direction at right angles to a crack. Figure 10 shows profiles of relative water content in the direction at right angles to the crack at 3cm from the end where water is applied. Each profile of 24, 48, 72, 120, 168, 312, 600, 1200, and 1800 seconds is shown. The results show that water reaches 4mm by 24 seconds without a relative water content increase. The migration length increases only a little until 48 seconds and the relative water content increases in turn. After that, both the migration length and the relative water content are increased by bits. The experiment result become similar to a traditionally known profile approximately only after 600 seconds.

Thus, water is not absorbed into concrete in the same way as is traditionally known at its early phase. Although there is difference of length scale, this behavior is as like water movement in a crack in this study.

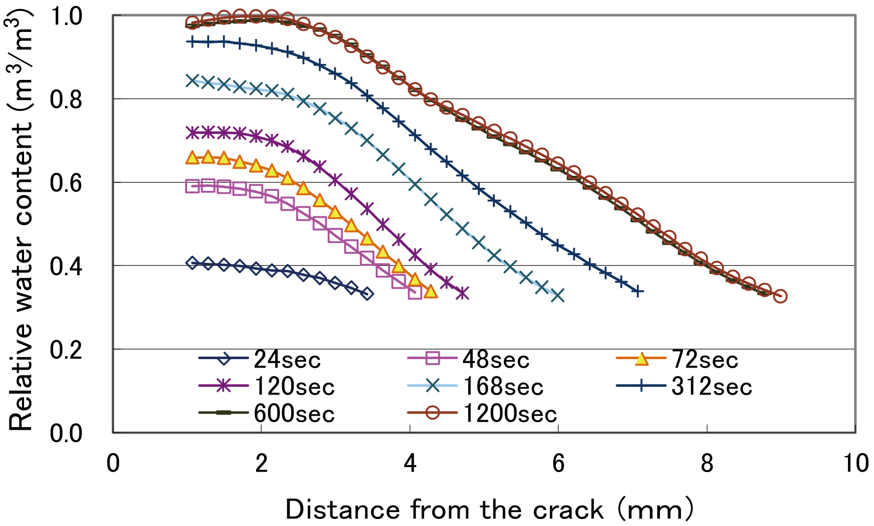

Figure 10. Profiles of relative water content C50-30

CONCLUSION

In this paper, we measured water movement by neutron radiography in order to understandhow water penetrates through cracks in concrete under unsaturated conditions. Water movement in both the horizontal and vertical directions of a crack from several terms of seconds to 1 hour are evaluated in particular by means of analyzing both the process of water migration length and relative water content profile.

The results obtained are summarized as follow.

(1) Water movement in a crack decelerates dramatically in minutes. So, water movement in a crack is divided into 2 main phases at the least.

(2) From the profiles of water content in the direction of a crack, the length of water movement along the crack increases before the relative water content is full at its early phase, and then, both the length and the relative water content slightly increase. The profile at the second phase is similar to the one for concrete.

(3) We studied water absorption into concrete from a crack, and confirmed as follows that the relationship between water migration length and the square root of time does not show linear performance.

(4) Water content profile in concrete is not as same as the popularly known profile at the early phase. Although there is a difference of length scale, it is similar to water movement in a crack in this study.

(5) It is possible for water movement in some kind of cracks in concrete to be treated in the same way as water absorption into concrete, which has more than 2 main phases. Applying to either a non-linear diffusion equation or the Washburn equation, it is necessary for models to be considered for such water movement.

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