QUANTIFICATION OF WATER PENETRATION INTO CONCRETE THROUGH CRACKS BY NEUTRON RADIOGRAPHY

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ABSTRACT: Improving the durability of concrete structures is one of the way for contributing to sustainable development of society, and it has also become a crucial issue from an environmental viewpoint. It is well known that moisture behaviour in reinforced concrete is linked to phenomena such as cement hydration, volume change and cracking caused by drying shrinkage, rebar corrosion, and water leakage that affect the durability of concrete.

In this research, neutron radiography was applied to visualize and quantify the water penetration into concrete through the cracks. As a result, it is clearly confirmed that Thermal Neutron Radiography can make visible the water behaviour in/near the horizontal/vertical crack and can quantify the rate of diffusion and concentration distribution of moisture with high spatial and time resolution. By making a detailed analysis it is observed that water penetrates through the crack immediately after pouring and its migration speed and distribution depends on the moisture condition in the concrete.

KEYWORDS: Neutron radiography, Non-destructive technique, Crack, Moisture absorption

1. INTRODUCTION

The moisture behavior in concrete which affect to every state from fresh to deteriorating is the one of most difficult phenomena to detect the real state. It is well known that the moisture behavior in concrete has much effect on hydration process, dimensional stability such as drying shrinkage, durability and so on.

The crack in concrete accelerate the ingression of water and/or other chemical substances into its inside and finally devastate its structural robustness. In fact, this ingression of water is one of the measure concern of housing and other buildings or structures that are required rigid water-tightness. In addition, the ingression of chemical substances such as chloride ion and oxygen induces the corrosion of reinforcement that sometimes jeopardizes the safety of structure. The crack in concrete is sometimes inevitable, and therefore, the effect of crack on service life of structure, such as the transportation of substances through the crack, has been studied by many researchers in the past. The process and mechanism of penetration of water through the crack is still unknown, while it is the most basic and important because ingestion of chloride ion and other substances are interdependent with water behavior.

Moisture behavior in concrete is commonly detected by humidity sensor such as ceramic, polymer or other electrical resistance that is sensitive to moisture content. But these methods always affect the concrete or cement matrix system because the sensor has limited size and this size restrains the system. Additionally the sensor always arouses suspicion of what is measured.
The application of the neutron radiography to cement based material goes back to the paper of 1972 by H. Rijonen whose study aimed at non-destructive monitoring of carbonation in concrete [1]. Recently, as the digitalization of graphics is promoted, several reports have been published [2-4], but there is no application of quantification of water in concrete and cement paste as well as visualization of water in cracked concrete.

In this research, to visualize and quantify the water penetration into concrete through cracks, some experimental study was performed by using neutron radiography. At the beginning, the quantitative capability of water content and the detectable depth with cement paste specimen were confirmed, and quantification method of the moisture content in concrete was proposed by defining the relative moisture content per cement paste. Then several concrete specimens, which have artificial bending crack and variety of water contents, were partially submerged in the water by a small bath attached on the surface of the specimen and penetrating water into concrete is visualized.

2. METHODS AND MATERIALS

2.1. Outline of a facility

Neutron radiography is based upon the fact that the neutron beam is attenuated due to the interaction of neutrons with the nuclei of the atoms in the object material according to scattering or absorption. The principle of the radiography in general is the recording of the radiation passing through an object by position sensitive converter. Because the attenuation of the radiation through the object depends on material thickness and density, the image contains qualitative and quantitative information about the structure and composition of the object.

The facility used for the entire experiment was the TNRF (Thermal Neutron Radiography Facility) installed at a research reactor, JRR-3M, of the Japan Atomic Energy Agency (JAERA).

The neutron flux was 1.2x10^8 (n/cm^2/sec). The TNRF is characterized by utilization of thermal neutron which can penetrate through various materials to large depths and various kind of research works not only in engineering but also in agriculture and biomedical sciences have been carried out using this facility [5].

The TNRF consists of a fluorescent converter, two quartz mirrors, one lens(105mm) and one C-CCD (Cooled Charge Coupled Device) camera as shown in Fig. 1. A full transfer type C-CCD camera with an effective array of 1008 pixels × 1024 pixels of 100mm × 100mm each was used. The spatial resolution is about 100 μm/pixel. It takes approximately 8.0 seconds to get one image including data transfer time and the work is exposed to the neutron for 1.2 seconds.

![Fig.1- Schematic illustration of TNRF](image1.png)

![Fig.2- Transmitted neutron radiograph of the concrete (w/c 50, 100×100×20mm)](image2.png)
A part of the neutrons irradiated to the sample scatters with the hydrogen, and the rest penetrate the sample and reach on a fluorescent converter (LiF/ZnS:Ag). The neutrons falling on the converter are transformed into a visible light in proportion to the flux and guided to the C-CCD camera using two quartz glass mirrors. The brightness of the image is then digitized by the image processor.

Fig. 2 shows a typical image obtained by NRF. Since the neutron is interrupted especially with the hydrogen atom, the obtained image becomes like the shadowgraph according to the existence of the hydrogen atom.

2.2. Experimental overview

In order to monitor the water behavior in a crack of concrete, the following experiments were conducted.

Mix proportion is shown in Table 1. Ordinary portland cement was used in this study. Concrete specimens of 100mm x 100mm x 20mm were made with a water-cement ratio of 0.65 and 50, and relative water contents of concrete are controlled to 0% (0%RWC), 30% (30%RWC) and 60% (60%RWC). After 24 hours from the casting, the specimens submerged in water at 20±2 degree C. After 28 days, 100%RWC specimens were stored in water still and 0%RWC specimens were dried at 105 degree C. After 5 weeks from casting, the neutron radiography testing was conducted. Compressive strength at 28 concrete age is 48.9N/mm² and absorption ratio which is obtained from oven dry at 105 degree C was 6.30%.

Fig. 3 shows the specimens’ specifications. Each specimen was cut out from a specimen of 100 x 100 x 400 mm. Horizontal and vertical crack was examined with 0.05 mm and 0.3mm width on the surface. Cracks of specimens are artificially produced by bending moment with high-rigidity loading machine and 2 pieces of broken specimens are fixed by adhesive aluminum tape with epoxy-bond for sealing the side on the crack. The crack width on the side surface of specimen is measured and controlled as 0.05 mm. And aluminum tank which supply water to specimen is attached by epoxy-bond on the surface of specimen including crack end. Every surface was sealed with adhesive aluminum tape without water supply surface.

![Fig. 3 - Specimens’ specifications](image3)

![Fig. 4- Relationship between moisture content per unit area and ln(I/I₀)](image4)
After measuring an initial intensity by the neutron radiography, the aluminum tank was filled with water from the filling port. A series of images were serially taken every eight seconds for 2 hours. To visualize the water penetration behavior through the crack, the differential images from initial time to time \( t \) were processed. Since the effect of scattered neutrons caused by the block of the water in the aluminum tank, the image just after pouring is used for the image of initial time.

### 2.3. Calculation of moisture content of concrete

From the statistical analysis of detected intensity of the neutron flux, the relationship between the intensity of the neutron beam and the characteristics of the sample can be described as follow

\[
I_t = I_0 e^{-(\lambda_c \rho_c \delta_c + \lambda_w \rho_w \delta_w)} \tag{1}
\]

where \( I_t \), \( I_0 \), \( \lambda_c \) (cm\(^2/g\)), \( \lambda_w \) (cm\(^2/g\)), \( \rho_c \) (g/cm\(^3\)), \( \rho_w \) (g/cm\(^3\)), \( \delta_c \) (cm) and \( \delta_w \) (cm) denote the intensity of the neutron flux with attenuating sample at time \( t \), the initial intensity of the neutron flux, mass-absorption coefficient of concrete, mass-absorption coefficient of water, density of concrete, density of water, the thickness of the concrete and the thickness of the water. In this paper, \( \lambda_c \) is containing the mass absorption coefficient of cement hydrate, including the bonding water, and unhydrated cement. And also, \( \lambda_w \) is containing the mass absorption coefficient of evaporative water as function of gel water, absorbed water, capillary water and water vapor.

Because \( \lambda_c \) and \( \lambda_w \) are constant characteristic value for each material and mix proportion in the thermal neutron, following equation holds between \( \lambda_c \rho_c \delta_c + \lambda_w \rho_w \delta_w \) and attenuation rate of neutron flux \( I_t / I_0 \).

\[
\ln(I_t / I_0) = \lambda_c \rho_c \delta_c + \lambda_w \rho_w \delta_w \tag{2}
\]

The differential moisture content in concrete from time 0 to time \( t \) can be described as equation (3) with a differential water as \( \Delta \delta_w \).

From the statistical analysis of detected intensity of the neutron flux, the differential moisture content in concrete from time 0 to time \( t \) can be described as equation (1) with a differential water as \( \Delta \delta_w \).

\[
\lambda_w \rho_w \Delta \delta_w = -(\ln(I_t / I_0) - \ln(I_0 / I_0)) = -\ln(I_t / I_0) \tag{3}
\]
The relative moisture content per cement paste is defined as follows:

$$\theta = \frac{\psi}{v_p \cdot \psi_s}$$  \hspace{1cm} (4)

where $\theta$, $\psi$, $\psi_s$, and $v_p$ denotes the relative moisture content per cement paste, moisture content (g/m$^3$), saturated moisture content [g/m3], volume fraction of paste (%).

The relative moisture content per cement paste was calculated by eq. (1)−(2) and relationship of Fig. 4. Fig. 5 shows the example of correction of paste volume fraction. The rugged graph due to the inhomogeneous of volume fraction of cement paste can be corrected to smooth graph with this procedure as shown in Fig.6.

3. RESULT AND DISCUSSION

4.1. Water behavior in the crack

Fig. 7 shows the results of images of water behavior in a crack. Each image shows the differential intensity of water that is converted to the gray-scale images. From these pictures, it is clearly confirmed that it makes visible the water in/near the crack with high resolution. And also it is observed that water penetrate through the crack immediately after pouring and its migration.

Fig. 7- Visualized water penetration through crack and diffusion from the crack
* water pool was attached on the left side of the specimen
speed and distribution depends on the moisture condition in the concrete. And with another detailed analysis, it is understood that the water has reached around 50mm depth in the horizontal crack, but 20-30mm depth in the vertical crack immediately after pouring water. From these result it is detected that water reaches to the 25-30mm depth in few minutes after it is exposed to water and in 30 minutes it reaches to the 80mm. This means water will be supplied to the rebar with few minutes’ scattered showers.

4.2. Water behavior around the crack

In Fig. 8 the change of the intensity of water in orthogonal oriented direction to the crack is shown. A horizontal averaged value in the area enclosed by the white-line-rectangle on the right image is plotted against the vertical coordinate. These plots illustrate the plausible results which can be predicted by former researches[3, 4] and make it possible to quantify the water movement from the crack surface to concrete matrix as well as from crack end to inside of crack.

From these results, it was suggested to be able to understand the water behavior in/near a crack of 0.05mm with high accuracy and high resolution that is assumed allowable limit of the water leakage.

4.3. Water supply from the crack to the rebar

Finally, to demonstrate the water supply from the crack to the rebar, a experimental research was conducted. The schematic of experiment and the result are shown in Fig. 9

Concrete specimens of 500x100x50mm were made with a water-cement ratio of 0.65 and 50, and relative water contents of concrete are controlled by oven dry. The water tank was set on the left side so that is assumed to be supplied from the crack.

Few second after injection of water, ingression of water was confirmed in the bleeding space under rebar. But after 2 hours from injection, ingression of water in the bleeding space was disappeared and water has moved into the matrixes. It can’t be explained with the situation that the tank was filled with water and the head difference of water head was still keep the initial state.
Water behavior in the concrete was very complicated. But by using the neutron radiography, the water behavior can be exquisitely observed and quantified with high special and time resolution.

5. CONCLUSION

1. With neutron radiography, it could be quantified the evaporable water behavior in the cementitious materials.
2. It is clearly confirmed that by using this technique, it makes visible the water behavior in/near the crack with high resolution.
3. And also confirmed that water penetrate through the crack immediately after pouring water and its migration speed and distance depends on the moisture condition of the concrete.
4. A experimental research was conducted to demonstrated the water supply from the crack to the rebar, and water behavior around rebar was obtained.

REFERENCES

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