Nondestructive Measurement for Water and Voids in Concrete with Compact Neutron Source*)

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The authors have developed a nondestructive inspection method using backscattered neutrons to detect voids and water in concrete with a RIKEN Accelerator-driven Compact Neutron Source (RANS). In this study, neutrons are emitted to a slab sample that consists of a concrete layer and an asphalt layer, and position distribution of backscattered neutrons are measured at the timing from 0.1 to 0.5 ms. The two-dimensional position of water and voids in the concrete plate under asphalt (5 cm) of the slab sample are detected.

Keywords: nondestructive testing, compact neutron source, back scattering, neutron imaging

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1. Introduction

Concrete is one of the main materials used in a lot of infrastructure. In the case of road bridges in cold regions and mountains, a recent topic is deterioration of concrete slabs under road surfaces. The combined effects of traffic loadings, sprayed deicing agents and rainwater under pavements damages the slabs; this damage is accelerated by water. Earlier deterioration than expected has been found in many places in Japan.

Among structural members for road bridges, one of the differences between slabs and other members is the pavement on the concrete surface. In other words, regular inspections of slabs are insufficient to monitor the deterioration of concrete under the pavement surface due to aging. However, the slabs are members that directly support users of road bridges and there is a significant risk of a serious impact on users if the slabs are damaged. Therefore, it is desirable to maintain slabs to prevent damage to third parties.

In this study, a backscattering (reflection) neutron imaging method to detect water and voids in concrete is applied to a non-destructive inspection method to understand the deterioration situation such as residence water and voids in concrete slabs under asphalt pavement surfaces from the road surface side. In the future, we aim to establish a technology that can understand the signs of deterioration of the soundness of concrete slabs.

Neutrons have large transmittance for heavy elements which have many electrons (Si, Fe and Ca that mostly constitute concrete) because they do not interact with electrons. Conversely, neutrons have a large interaction with hydrogen nuclei. So, neutrons have suitable properties to measure the presence and distribution of water in concrete structures.

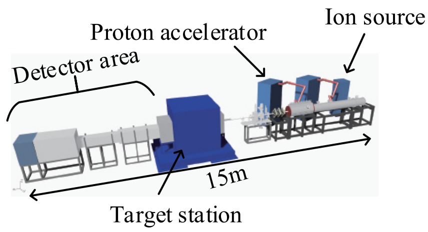

Fig. 1 RANS, RIKEN Accelerator-driven compact Neutron Source.

RANS (Riken Accelerator-driven compact Neutron Source) is developed for industrial use and nondestructive inspection of infrastructure. Figure 1 shows the overview of RANS. Neutrons are generated by the “Be (p, n), B” reaction with 7 MeV proton beams, pulse width of about 20 to 180 µs, repetition efficiency of 20 to 200 Hz, and a maximum average current of 100 µA. A long-lived Be target has been used for stable and continuous operation from 2013 [1]. The features of RANS are: proton beams pulse width of about 20 to 180 µs, repetition efficiency of 20 to 200 Hz, a maximum average current of 100 µA. Figure 2 shows the neutron energy spectra of RANS [2]. The maximum neutron energy is 5 MeV and the minimum neutron energy is extended to under 10 meV with a 4-cm-thick polyethylene moderator. It is an open space up to about 6 m from the target station, and samples, detectors and shields (camera box, neutron beam pipe, etc.) can be installed.

Neutron beams have been used for limited purposes such as neutron imaging for experiments at laboratory-level nuclear reactors, as well as for structural analysis of materials by making use of the properties of neutron waves with energy levels of 100 meV or less, and elemen-

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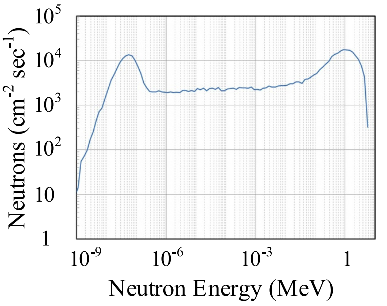

Fig. 2 RANS neutron energy spectrum at 5 m away from the moderator.

tary analyses using neutron capture reactions of atomic nuclei. The promises of such experiments were quite limited, that is, only for facilities with a nuclear reactor. Now, many more advanced applications are expected for neutron sources in line with the start of operation of a large-intensity proton accelerator facility (J-PARC Japan, ISIS UK, PSI Switzerland and so on), as a neutron source utilizing a large accelerator. However, in spite of the desired frequency to use the neutrons, the resource shortage is one of the major issues for promotion of the use of neutrons since such large facilities are available only for several days a year. Under these circumstances, RANS are developed as a compact neutron source available at any time in facilities of corporate users or universities [2].

2. Development of Non-Destructive Method by Radiation Transport Simulation

In the conventional non-destructive inspection method using neutron transmission, the sample should be interposed between a neutron source and a detector [3]; however, the applicable environment is limited. In order to solve this problem, we developed a new method to use backscattered (reflected) neutrons (Fig. 3) [4]. In this method, the detector is placed between the neutron source and the sample. It can be applied to the nondestructive inspection of road bridge decks, airport runways and tunnel walls. Neutron and hydrogen nuclei have strong interaction, and neutron energy loss during elastic scattering is large because the mass is close to the neutron. Therefore, the hydrogen nuclei (water) in the concrete, increases the low energy (0.01 to 1 eV) backscattered neutron returning by scattering when neutrons with kinetic energy of about 1 MeV enter the concrete target. The amount of radiation for low-energy neutrons mainly depends on the hydrogen density of the sample, and its measurement helps to visualize the distribution of the moisture content inside.

The tracking and energy change of neutron scattering in concrete from incidence to emission was calculated by radiation transport simulation. The simulator is generated

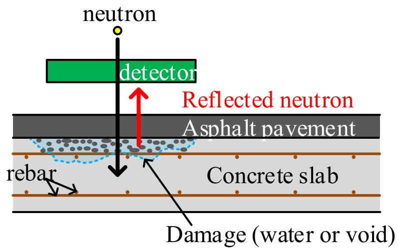

Fig. 3 Backscattered neutron method.

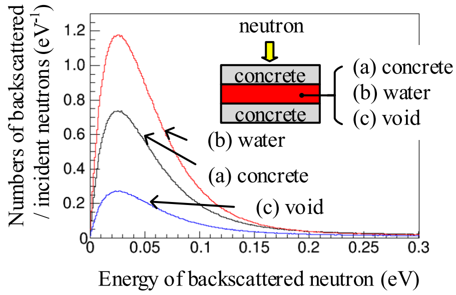

Fig. 4 Simulation results of energy spectrum of backscattered neutrons.

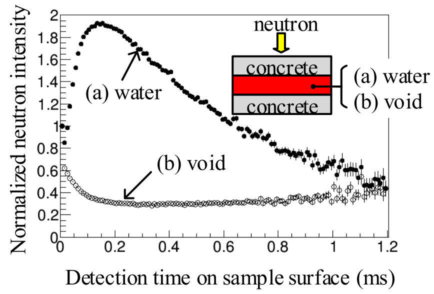

Fig. 5 Simulation results: time distribution of normalized intensity of backscattered neutrons with normal state.

using geant4 [5]. The elemental composition of each general material is applied for this study, assuming concrete W/C = 0.55 using ordinary Portland cement, 5% for the bitumen, 4% for air and aggregate for the rest of the calculation [6].

Figure 4 shows the energy spectrum of neutrons radiated from the sample surface when 1 MeV neutron is incident. The figure of the backscattered neutrons with low energy ($E < 0.2$ eV) increases with water and decreases with voids. Figure 5 shows the time distribution of the amount of backscattering neutrons measured in the same range for the acrylic part or voids, which is 60 mm thick and are placed between two concrete blocks of 60 mm thick, and the intensity is normalized by that of the normal state that has neither acrylic nor voids. The intensity of the backscattering neutrons increases from the incident for the range up to 1 ms due to water and decreases due to voids. Water and voids in the concrete could be detected by measurement of the neutrons at the timing.

3. Experiment with Compact Neutron Source "RANS"

The experiment is a continual measurement for five minutes per one sample, using a neutron generated with a proton pulse width of 30 µs, a repetition frequency of 150 Hz, and an average current of 19 µA. However, due to the limit of figures for the detector to count, a boron-containing polyethylene block with a thickness of 5 cm is positioned and the neutron beam intensity is reduced to about 10% before being injected. The detector is a position sensitive detector (PSD) in which eight gas tube chambers filled with 10 atm of He-3 are arranged in parallel, and it has a sensitive area with a diameter of 12.7 mm and a length of 600 mm [7]. The coverage of the sample image is 480 pixels for detection, which was divided into 60 sections toward a width of 600 mm, and 8 sections, per tube, for a length of 102 mm. The lateral width of the sensitive area is equal to the sample, and it is positioned to make close contact with the neutron incident side surface of the sample. A time resolution of a few microseconds and a position resolution of about 1 cm can be measured for each neutron.

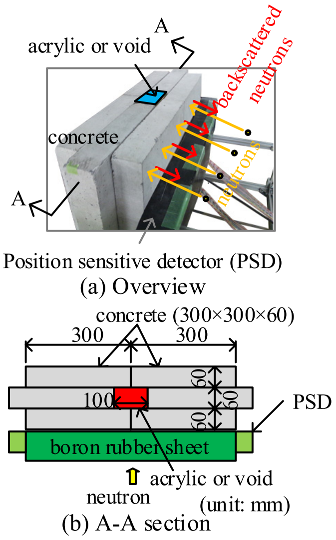

Fig. 6 Setup of the experiment.

3.1 Measurement of defects in concrete blocks [4]

Figure 6 shows the setup of the experiment. Concrete, with a size of 6 cm×30 cm×30 cm, is arranged in two rows in the thickness direction and three layers toward thickness direction, which has a void for 10 cm × 30 cm (thickness of 6 cm) or an acrylic block (thickness of 5.5 cm) in the middle. The experiment is conducted in order of: the neutron detector is fixed onto the center of one side, then neutrons are entered from the face, and the distribution of time and location for individual neutrons is measured, to observe the figures to compare to a normal state without water or voids to the state over time.

Figure 7 shows a two-dimensional histogram showing the comparison of the position and intensity distribution of backscattered neutrons and the location of the acrylic layer and voids inside the sample. This experiment is to observe the distribution of the intensity ratio by measuring the backscattered neutrons at the timing ranging from 0.1 to 0.5 ms per pixel, and by shifting the position of the acrylic or voids from the center to the left (Fig. 7 (a)). The degree of the intensity change due to the internal acrylic reaches up to 4 times that of the normal state, and up to about 0.7 times with the voids with the sample used in

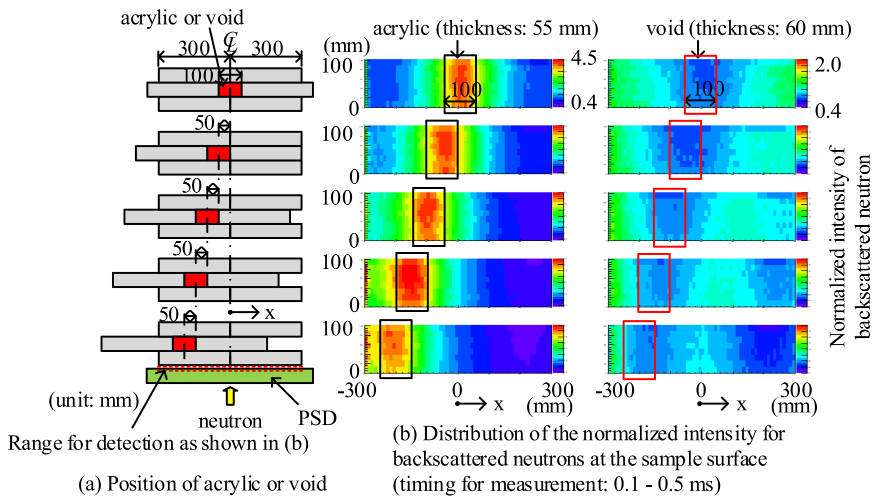

Fig. 7 Experimental results: imaging of concrete with acrylic or voids by the backscattered neutron method (the intensities of backscattered neutrons were normalized with the normal state).

this experiment. The figure distinguishes the colors for the cases of acrylic and voids in the range from 0.4 to 4.5, and from 0.2 to 1.2, respectively. As shown in bright and dark colors for high and low intensity, the position of the acrylic (voids) and the intensity level of the backscattering neutron (increase or decrease) are consistent. Hence, this result reveals that the backscattering neutron is sufficient to sense the acrylic (water) and the voids under concrete in the experiment.

3.2 Measurement of a defect under asphalt pavement

A road bridge deck with asphalt pavement samples as shown in Fig. 8 was prepared and experiments were carried out (Fig. 9) to investigate the effectiveness of this method for non-destructive inspection of road bridge defects. For the deck sample, asphalt mixture plates (thickness: 5 cm) are stacked on an RC plate with a thickness of 6 cm and fixed with an iron frame. A hole with a width of 9.5 cm × 7.5 cm penetrates as a defect in the RC board. The defect portion with a depth of 3 cm from the contact surface with the asphalt mixture is gaps or filling with an acrylic block, and the remaining portion is filled with concrete blocks. An acrylic block is used as a substitute for water because it has a hydrogen density equivalent to that of water and is easy to handle. Neutron is incident from a moderator 5.52 m upstream from the sample surface. Backscattered neutron intensity is measured by dividing it into four areas of 60 cm × 10 cm at a time, and normalized by measurement values at the area furthest from the defect without the acrylic block (PSD position 4 shown in Fig. 8), and the neutron intensity ratio was obtained.

Figure 10 shows a two-dimensional histogram of the backscattered neutron intensity ratio at the timing from 0.1 to 0.5 ms. The backscattered neutron intensity ratio measured on the surface of the asphalt above of the acrylic block has locally increased to about 1.5 times. The asphalt mixture, which is a hardened aggregate with asphaltene, contains carbon, nitrogen and hydrogen derived from petroleum, but has a hydrogen density close to that of concrete cured by a hydration reaction of water and cement. Therefore, it is considered that acrylic under an asphalt pavement could be detected as well as in experiment using plain concrete. From the above, it is shown that this measurement, which is sensitive to the hydrogen nucleus may be applicable even under an asphalt pavement. For practical use, the position resolution determined by multiple scattering due to internal scattering of neutrons and the size limit of measurable voids is being studied.

Fast neutron of a frequency of less than 1 kHz and a pulse width of less than 0.1 ms are required to measure the time of the backscattered neutron at 0 - 1 ms (see Fig. 5), so, laser-driven neutron source would be usable. The higher the flux, the better. However, limit of figures for the detector to count is a bottleneck, now.

4. Conclusion

The authors have developed a nondestructive inspection method with backscattered neutrons to detect voids and water using a compact neutron source, and the effectiveness for defect detection in road bridge decks was investigated. The position of water and voids in an area 6 cm

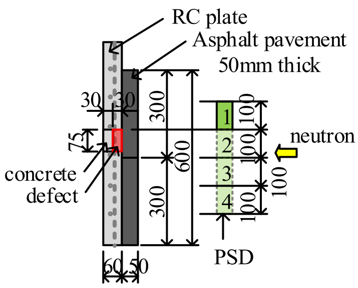

Fig. 8 RC slab sample with asphalt pavement.

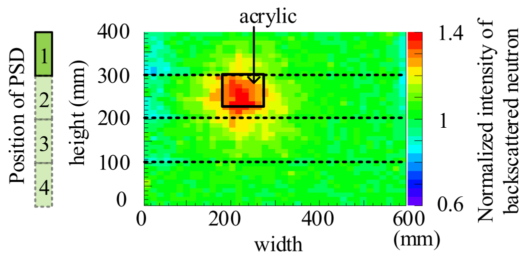

Fig. 10 Distribution of the normalized intensity for backscattered neutron.

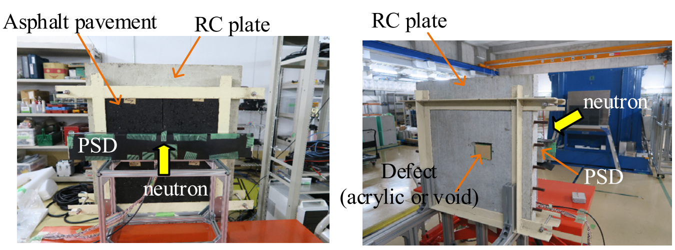

Fig. 9 Experimental setup.

below the surface of the concrete was detected. This was provided by the intensity change of backscattered neutrons measured at the timing from 0.1 to 0.5 ms.

The sample of asphalt paved road bridge concrete deck slab was prepared and the two-dimensional position distribution of the intensity change of backscattering neutrons due to the internal acrylic block and void was measured at the timing. It shows that this method is effective for detecting the position of 3-cm-deep water or voids under 5-cm-thick asphalt pavement.

In addition to development of a portable accelerator neutron source, we will improve detectors and optimize measurements, and will also advance the measurement of large areas in a short time. It is possible to install detectors on the same side as the installation of irradiation equipment (neutron incident) in this method. Highways, airport runways, tunnels, and railway ties can be inspected with the backscattered neutron method in the future.

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