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Scientific paper

Nondestructive Measurement Method to Detect Water/Void inside Slabs using Compact Neutron Source by Backscattered Neutrons

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Abstract

A nondestructive inspection method which is in type using backscattered neutrons to detect void and water in concrete with RIKEN Accelerator-driven Compact Neutron Source (RANS) is developed. In this method, it is not necessary to be interposed the sample between the radiation source and the detector as in the conventional method using neutron transmission. The position of water and void in the concrete are measured from the intensity change of the backscattered neutrons selected from the incident up to 1 ms. This study reveals that it is possible to observe the two dimensional distribution of water or void inside slabs up to 6 cm below the slab surface.

[This paper was presented at the 9th Symposium on Decks of Highway Bridges (JSCE, Japan Society of Civil Engineers) in November 2016.]

1. Introduction

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 slab is a member that directly supports users of road bridges and there is significant risk of a serious impact on users if it is damaged. Therefore, as it is desirable to maintain slabs to prevent damage to third parties, new technology is necessary to regularly monitor the deterioration of the slab under the pavement surface.

Since it is recognized that the deterioration of the concrete slab can be due to the negative influence of water (Matsui 1987), "Waterproof layer of reinforced concrete slab on road bridge: Design and Construction (1987)" first specified the full-scale provision of waterproofing for slabs. However, many cases of deterioration have been reported such as delamination, spalling or falling of concrete lumps (Fujiwara 2014) to now. Furthermore, NEXCO technical committee report (2014) indicates that the degradation of structural performance due to a complex reasons such as salt damage, and it is even more difficult to sustain the soundness of RC slabs compared to PC slabs.

Based on awareness of the above issues, the authors study the effectiveness of neutron sources, as one of the methods of nondestructive inspection, to apply to concrete from the road surface to show the status of deterioration of concrete slabs that might be in progress under pavements. In the future, we aim to establish method to monitor any signs of deterioration of concrete slabs, such as delamination, peeling or spalling that might result in falling of concrete lumps or cave-in of slab.

2. Development of inspection devices of concrete slabs

2.1 Neutrons suitable for inspection of concrete

A neutron beam is a type of radiation of neutrons, one of the particles to constitute the nucleus, incident by kinetic energy. As the interaction between radiation and substances varies depending on particle type or energy, such difference affects transmittance and reflectance when radiation enters a substance. The nondestructive inspection technology using radiation is to measure the amount of radiation transmitted to the sample to emit outward, and image the distribution of such elements, its concentration, or size by calculating the difference of transmissivity (or reflectivity) of each element inside the sample. Therefore, it would be necessary to select a type of radiation that is sufficiently transparent over the entire area of the sample while the strength of interaction among different substances is quite different in order to have sufficient shading when being imaged.

The neutron beam does not interact with electrons and the strength of the interaction depends on the nuclear species. The permeability of various neutron beams also varies. The neutron beam has high permeability in a medium containing a large amount of elements such as silicon and calcium, and enters relatively deeply into these elements. At the same time, neutrons have some advantages, such as strong interaction with light ele-

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ments such as hydrogen, lithium, boron, and high sensitivity to water and organic matter. In this regard, it can be said that neutron beams have properties suitable for observing the presence and distribution of water in concrete structures.

Furthermore, high permeability is required for cases of concrete for large-scale structures, which are used for infrastructure. RANS simultaneously generates neutrons with an 8-digit energy range. Therefore, users may select the neutron energy region depending on the characteristics and phenomena of materials for measurement. For example, since there is a successful world-first case of a neutron at the energy level of 0.01 - 0.1 eV to visualize corrosion under coatings of steel and existence of water (Yamada *et al.* 2014), the joint project with industries is ongoing with this technology. Meanwhile, it has been confirmed that the steel materials can be measured by utilizing the permeation property of neutrons with energy of 1 MeV or more (Otake and Sunaga 2014; Otake 2015) through concrete with a thickness of 30 cm. However, cases are limited with the permeation method since it would be necessary to sandwich the target between the neutron source and the detector. In this research, therefore, we began to develop a new method.

2.2 Improvement of device usage

Figure 1 shows the RIKEN Accelerator-driven compact Neutron Source (RANS) used in this study. The development policy of RANS is to make the entire system, including shielding, compact so as to make it easy to use for material development and non-destructive inspections, and so forth.

In the course of the development of RANS, we first designed a neutron source by a “Be (p, n), B” reaction which adopts proton beams with high neutron generation efficiency, using a long-lived Be target (Yamagata *et al.* 2015), which was then used for stable and continuous operation for two years from 2013 (Otake *et al.* 2015). The feature of RANS are: proton beams at energy of 7 MeV, pulse width of about 20 to 180 μ s, repetition efficiency of 20 to 200 Hz, the maximum average current of 100 μ A, and the shield, combining boron polyethylene and lead. The maximum length of the neutron beam line is approximately 6 m. **Figure 2** shows the neutron energy spectra of RANS at 5 m away from the moderator (Ikeda

et al. 2016), which was simulated by PHITS code (Sato *et al.* 2013).

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 of 100 meV or less, and elementary analyses using neutron capture reactions of atomic nuclei. The promises for such experiments were quite limited, 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 named J-PARC, Japan, as a neutron source utilizing a large accelerator. However, in spite of the desired frequency to use the

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

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 (Ikeda *et al.* 2015, 2016).

2.3 Compact and lightweight design for on-site applications

The current RANS is a stationary type, while it is installed in a radiation-controlled area, and is portable even for outside use as it was designed from the initial model having radiation shields and safety coverage to control

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

Table 1 Elemental composition of concrete and asphalt mix used for the simulation.

	Density (g/cm ³)	Elemental composition (wt%)
Concrete	2.2	O: 0.5446, Si: 0.346, Ca: 0.0446, Al: 0.0348, Fe: 0.0143, H: 0.0103, Mg: 0.0022, K: 0.0022, C: 0.001
Asphalt mix	2.35	O: 0.48, Si: 0.42, C: 0.085, H: 0.01, N: 0.005

risks. According to the current Radiation Hazards Prevention Law of Japan and related laws and regulations, it is stipulated that devices including linear accelerators less than 4 MeV can be used for inspection of bridges, and so forth, as long as they are approved by the Nuclear Regulatory Commission. Backed by this, the development of RANS continues to be further downsized and its safety improved, with the aim of applying it for nondestructive inspections of infrastructure like bridges, such as for deterioration diagnosis of concrete slabs.

Firstly, downsizing is one of the challenges in order to use vehicles equipped with such neutron sources for inspection of infrastructure such as bridges. The weight of the target station of the transportable compact neutron source with less than a 4 MeV proton beam, currently in design, is about 700 kg according to the radiation transport calculation. For further downsizing and safety improvement for outdoor use, the development of this method is ongoing to reduce the radiation generated. This challenge is to realize transmission images much clearer than ever through advancement of the technologies of a detector with high sensitivity and the image analysis technology as well as realizing neutron beams at shorter pulses, even though the output of the neutron beam is reduced. Safety measures are also considered to avoid the danger of moving the device (that is, impacts from vibration or collision, and scattering of radioactive substances) by all means. Furthermore, to safely use the device outdoors, the device is designed to completely stop radiation by shutting off the power. Regarding radiation shielding, we are also developing a system including shielding capabilities to suppress radiation to the level of natural radiation even when the compact neutron source for the nondestructive observation system is in operation.

In the conventional nondestructive inspection method using neutron transmission, the sample should be interposed between a neutron source and a detector (de Beer *et al.* 2004; Justnes *et al.* 1994; Kawabata *et al.* 2004;

Otake *et al.* 2017). however, the applicable environment is limited. In order to solve this problem, we developed a new method to use backscattered (reflected) neutrons. In the new method, the detector is placed between the neutron source and the sample.

3. Development of simulation-based measurement method

When neutrons with kinetic energy of about 1 MeV are entered into the concrete target, the neutrons go backscattering with the atomic nuclei in the substance, and lose a part of their kinetic energy and reduce speed of movement, as well as to change the direction of their motion. This cycle of movement continues until the neutrons are emitted from the substance, which then shows an energy distribution with a peak around 20 to 50 meV. The efficiency of this reaction depends on the nuclear species and its density. From the viewpoint of mechanics, the amount of energy incurred from collision with the hydrogen nucleus, which the mass is similar to neutron, would be the largest because it is a two-body collision. For this reason, the amount of radiation for low-energy neutrons mainly depends on the hydrogen density of the medium, which helps to visualize the distribution of the moisture content inside by calculating the figures. This paper describes the study of backscattered neutrons, which are entered into a sample and finally emitted from the incident surface of the sample after multiple scatterings. **Figure 3** shows the image of this experiment in contrast to the measurement of the transmitted neutrons.

Since the transmittance and reaction rate of radiation depend on the species and energy of the radiation, it is necessary to select one appropriately. The detectors used for measurement of radiation also vary in terms of the measurable range of energy and measurement efficiency. With RANS, as neutrons for up to 5 MeV are injected and it is widely distributed to 10 meV while repeating elastic

Fig. 3 Schematic view of neutron measurement method.

scattering. Thus, the authors predict an appropriate range of energy and reflection timings from a simulation based on the radiation transportation calculation using the reaction cross-section table of each nucleus and neutron that have already been measured, and select a detector and measurement method suitable for such experiments in this study. The simulator is generated using geant4 (Agostinelli *et al.* 2003). A nuclear data (cross section of elastic scattering, absorption and other reactions for each nuclear species) of ENDF is used for the neutron transport model with energies lower than 20 MeV in the geant4 simulation. **Table 1** shows the element composition of the concrete and bitumen used for the simulation. In this study, the hydrogen density contained in concrete and bitumen mainly impacts the simulation result. Therefore, the standard elemental composition of each general material is applied for the simulation. The chemical composition of concrete is referred to the report by JAEA-Data/Code (2009) and Tashiro (1994), and the chemical composition of asphalt is referred to the results of the elemental analysis of straight asphalt produced from a type of crude oil (Abe 1972).

In this simulation, three concrete boards (6cm thick and 1 m×1 m width) are stacked and the momentum, kinetic energy and time of flight of neutron with scattering is calculated. The concrete board in the middle is replaced to water or void, and the intensity change of backscattered neutron is estimated. **Figure 4** shows the energy spectrum of neutrons radiated from the sample surface when 1 MeV neutron, which is also in RANS, is emitted toward the core of the sample. The figure of the backscattered neutrons with low energy ($E < 0.2$ eV) increases with water and decreases with void. Compared to the high-energy neutrons radiated with fewer scatterings, the low energy neutrons radiated after many scatterings strongly depends on the medium inside the sample. Thus, if the number of changes for backscattered neutrons can be measured in this energy region, it should be possible to detect water and void inside structures. A concrete sample without water or void is defined as a normal sample. The measured intensity of backscattered neutron of each sample is normalized with that of the normal sample. The change of intensity due to existence of water or void from normal sample is obtained.

Figure 5 shows the time distribution of the ratio of intensity of backscattered neutrons against the state standardized as that without water or void. The low energy neutrons are radiated from the sample over a longer period of time than that of high-energy neutrons. As the low energy neutrons are radiated mainly at an interval of 0.05 to 1 ms, water and void inside the structure can be detected and monitored as the change of intensity. The timing changes depending on the material and shape of the sample. The time distribution of the backscattered neutron from the incidence should be measured using a pulsed neutron source to select a time for measurement and the neutron with the information of the sample.

Figure 6 shows the neutron beam intensity ratio,

which is standardized by the value of the sole sample of concrete to identify the figures of the backscattered neutrons radiated at an interval from 0.1 to 0.6 ms. The same as the ones shown in **Figs 3** and **4**, the study applies three blocks of concrete with a size of 1 m × 1 m with a thickness of 6 cm, which are piled up and the surface layer contains a bitumen, and the intermediate layer is regarded to be water or void. The results show the strength increase of 1.8 times with water, and the strength reduction by the void for 0.4 times. The element composition ratios of the concrete and bitumen used in the

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.

Fig. 6 Simulation results: normalized intensity of backscattered neutrons for some materials.

simulation are shown in **Table 1**. The ratio of hydrogen within the bitumen in this experiment is 3.8 % higher than that of concrete but the level of backscattering neutron obtained by this simulation, which is strongly sensitive to the hydrogen nucleus density, increases by 6.5 % compared to that only with concrete. Since this difference is smaller than the signals of water and void, concrete is used for all the experiments to follow, not the bitumen. Furthermore, an acrylic material, which contains hydrogen in the same density as water, is used instead of water for ease of handling in the experiment.

4. Reflective imaging of water and void inside slab samples using the accelerator-driven compact nuclear source

An experiment is conducted to demonstrate measurement through nondestructive imaging of water and void inside the slab using neutrons with RANS. **Figure 7** shows the setup of the experiment. Concrete, in 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 are measured, to observe the figures to compare to a normal state without water or void to the state over time. Neutrons are incident from a moderator located 336 cm upstream from the sample surface.

For the detector, a set of 8 gas pipe chambers containing He^3 of 10 atm, in size of a diameter of $\phi 12.7$ mm and a length of $\times 600$ mm, are aligned in parallel. Total sensitive area is $\times 600$ mm and $\times 100$ mm. The lateral side of the sensible surface contacts the surface of the neutron at one side to emit the neutron in the same manner as the sample. The experiment is to measure a position resolution of about $\times 10$ mm for each neutron. As the detection efficiency increases as the energy decreases, which is about 90% at 10 meV, 50% at 100 meV and more than 90% for lower than 10 meV. It is suitable for measuring

the energy range predicted by simulation (**Fig. 4**).

The experiment is a continual measurement for five minutes per unit time, using a neutron generated from a rectangular pulse proton beam with a 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 placed and the neutron beam intensity is reduced to about 10 % before being injected.

Figure 8 shows the time distribution of the amount of backscattering neutron measured in the same range for the acrylic part or void, and the intensity ratio comparison to the standard state which has neither acrylic nor void. The time of neutron hit on the PSD from beam incident were measured for every pulse beam. As predicted in the simulation (**Fig. 5**), the intensity ratio of the backscattering neutron increases from the incident for the range up to 1 ms due to water and decreases due to void. Therefore, the water and void in concrete can be detected by measurement of the backscattered neutron at the timing when the intensity ratio has a peak to the time distribution. The results of the experiment and the simulation might not be completely the same, in terms of the intensity ratio from the normal state to that with water or void. While it is thought that such difference is due to the difference of the moisture content of concrete, the

Fig. 8 Experimental results: time distribution of the normalized intensity of backscattered neutrons with the normal state.

Fig. 7 Setup of the experiment.

ratio of intensity between the void and water is almost five times that of the normal state at the maximum, which the results are consistent. Accordingly, the experiment results of the change in the strength when water exists in samples explain that the method applied to this study may be able to capture the images of ponding under pavements, which could be a cause of falling of concrete lumps and cave-in of slabs.

Figure 9 (b) illustrates a two-dimensional histogram showing the comparison of the position and intensity distribution of backscattered neutrons and the location of the acrylic layer and void 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, as shifting the position of the acrylic or void from the center to the left (**Fig. 9 (a)**). As shown in **Fig. 8**, the degree of the intensity change due to the internal acrylic reaches up to 4 times from the normal state, and about up to 0.7 times with the void with the sample used in this experiment. The figure distinguishes the colors for the cases of acrylic and void 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 (void) 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 void under concrete in the experiment.

The position (spatial) resolution depends on the multiple scattering of neutron in the sample, and the resolu-

tion decreases as the measurement in the deep position. For practical use, the position resolution and the size limit of measurable voids is being studied.

5. Conclusion

The authors have developed a nondestructive inspection method with backscattered neutrons to detect void and water in concrete using RANS, the RIKEN accelerator-driven compact neutron source. The position of water and void in the area 6 cm below the surface of the slab were observed in the form of two-dimensional distribution. It was provided by the intensity change of backscattered neutrons measured at the timing from 0.1 to 0.5 ms.

It is not necessary to be interposed the sample between the radiation source and the detector as in the conventional method using neutron transmission. Thus, the results of the study show the potential of this method to be one of the future methods for nondestructive inspection of concrete slabs of road bridges, airport runways and tunnel walls. There is already a successful case of another study, applying the same method as this study, to detect acrylic blocks with a thickness of 5 mm below concrete with a thickness of 10 cm, and ones with a thickness of 20 mm under concrete with a thickness of 20 cm. This study will be followed by the development of a transportable type of accelerator neutron source, aiming for improvement of the detector and optimization of the measurement method in order to advance the capability of detecting deterioration damage in the slabs. Along

Fig. 9 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.)

with the development of radiation sources, we plan to move to the pilot-testing phase towards societal implementation of this method.

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References

- Abe, Y., (1972). "Lecture of asphalt technologies for civil engineers (Road): Session 2. Manufacturing method and composition of asphalt." *Asphalt*, 92-93 Combined Number, 46-52. (in Japanese)
- Agostinelli, S., Allison, J., Amako, K., Apostolakis, J., Araujo, H., Arce, P., Asai, M., Axen, D., Banerjee, S., Barrand, G., Behner, F., Bellagamba, L., Boudreau, J., Broglia, L. and Brunengo, A., (2003). "Geant4, A Simulation Toolkit." *Nuclear Instruments and Methods in Physics Research Section A*, 506(3), 250-303.
- Fujiwara, H., (2014). "Research report on road bridge concrete slabs affected by water." *J-BEC Report*, 10, 11-17. (in Japanese)
- de Beer, F. C., Strydom, W. J. and Griesel, E. J., (2004) "The drying process of concrete: a neutron radiography study." *Applied Radiation and Isotopes*, 61, 617-623.
- Ikeda, Y., Takamura, M., Taketani, A., Sunaga, H., Otake, Y., Suzuki, H., Kumagai, M. and Oba, Y., (2016). "Prospect for application of compact accelerator-based neutron source to neutron engineering diffraction." *Nuclear Instruments and Methods in Physics Research A*, 833, 61-67.
- Ikeda, Y., Takamura, M., Taketani, A., Sunaga, H., Otake, Y., Suzuki, H., Kumagai, M., Oba, Y. and Hama, T., (2015). "Measurement of neutron diffraction with compact neutron source RANS." *IL NUOVO CIMENTO C*, 38(6), 177.
- Japan Atomic Energy Agency, (2009). "Second version of data collection part of nuclear criticality safety handbook." *JAEA-Data/Code 2009-010*. (in Japanese)
- Justnes, H., Bryhn-Ingebrigtsen, K. and Rosvold, G. O., (1994). "Neutron radiography: an excellent method of measuring water penetration and moisture distribution in cementitious materials." *Advances in Cement Research*, 6(22), 67-72.
- Kawabata, Y., Nakano, T., Hino, M., Sunohara, H., Matsushima U. and Takenaka, N., (2004) "High contrast neutron radiography with optical devices in Kyoto University reactor." *Nuclear Instruments and Methods in Physics Research A*, 529, 238-242.
- Matsui, S., (1987). "Fatigue strength of RC slab of road bridge affected by moving load and water." *Proceedings of the Japan Concrete Institute Annual Convention*, 9(2), 627-632. (in Japanese)
- NEXCO (East, Central and West Nippon Expressway Company Limited), (2014). "Technical committee report on long-term maintenance and renovation of highway assets." (in Japanese)
- Otake, Y., (2015). "Towards health diagnostics with non-destructive inspection with quantum beam: RANS, RIKEN Accelerator-driven Compact Neutron Source." *Journal of JSNDI*, 64(5), 221-224. (in Japanese)
- Otake, Y. and Sunaga, H., (2014). "Nondestructive inspection of bridges." *JACIC Information*, 110, 62-69. (in Japanese)
- Otake, Y., Uesaka, M. and Kobayashi, H., (2015). "Compact neutron source." In: A. W. Chao and W. Chou, Eds. *Reviews of Accelerator-Science and Technology*, New Jersey. World Scientific Publisher, 8, 181-208.
- Otake, Y., Seki, Y., Wakabayashi, Y., Ikeda, Y., Hashiguchi, T., Yoshimura, Y., Sunaga, H., Taketani, A., Mizuta, M., Oshima, Y. and Ishida, M., (2017). "Research and development of a non-destructive inspection technique with a compact neutron source." *Journal of Disaster Research*, 12(3), 585-592.
- Sato, T., Niita, K., Matsuda, N., Hashimoto, S., Iwamoto, Y., Noda, S., Ogawa, T., Iwase, H., Nakashima, H., Fukahori, T., Okumura, K., Kai, T., Chiba, S., Furuta, T. and Sihver, L., (2013). "Particle and Heavy Ion Transport Code System PHITS, Version 2.52", *J. Nucl. Sci. Technol.*, 50, 913.
- Tashiro, T., (1994). "Moisture in hardened concrete." *Concrete Journal*, 32(9), 12-15. (in Japanese)
- Yamada, M., Otake, Y., Taketani, A., Sunaga, H., Wakabayashi, T., Kono, K. and Nakayama, T., (2014). "Non-destructive inspection of under-film corroded steels using a compact neutron source." *Tetsu-to-Hagane*, 100(3), 429-431. (in Japanese)
- Yamagata, Y., Hirota, K., Ju, J., Wang, S., Morita, S., Kato, J., Otake, Y., Taketani, A., Seki, Y., Yamada, M., Ota, H., Bautista, U. and Jia, Q., (2015). "Development of a neutron generating target for compact neutron sources using low energy proton beams." *Journal of Radioanalytical Nuclear Chemistry*, 305(3), 787-794.