Committee Report: JCI- TC191A

Technical Committee on Inspection and Assessment of Concrete by Neutron Beam

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Abstract

In recent years, studies have been conducted to apply neutron beams to concrete, as they have stronger permeability than X-rays. They enable to obtain important information related to the soundness of concrete structures, as (1) observation of water transport over time, (2) detection of internal defects (penetrated water and voids), and (3) non-destructive measurement of chloride, etc., can be conducted quantitatively with them. The purpose of the activity of this committee was to utilize neutron beams as (1) a screening technique of deformed parts of concrete structures, (2) an assessment technique of quality, deterioration, and damage state of concrete, and (3) to prepare scenarios of maintenance systems of concrete structures based on the results.

Keywords: Neutron beam, non-destructive test, water, chloride, maintenance

1. Introduction

Concrete structures constitute numerous infrastructures and are so important for people living on them. A reason for the extensive use of concrete structures is their high durability when properly designed and constructed. However, there are several cases of rapid deterioration, a large number of the structures constructed in the high growth period are aging all at once, and the importance of maintenance of structures has been recognized. The situation is similar in the buildings, and considering that reinforced concrete (RC) and steel reinforced concrete structures have a long service life, they are expected to compose a large share of the housing stock in the future.

Technological improvement of the inspection and assessment for maintaining these enormous social capital stock and buildings, and efficiency improvement and upgrading of the inspection technique, have become critical issues. To prevent accidents, minimize the life cycle cost of structures through preventive maintenance, and prevent the deterioration of asset values under severe financial conditions and the decrease in the number of skilled engineers, the efficiency and sophistication of detailed investigations is expected to be improved through technical support using new technologies such as non-destructive investigations and the development of technologies for detailed investigations.

Under such circumstances, attempts have been made to investigate the condition of concrete using neutron beams. Neutron beams have stronger permeability than X-rays, and utilization methods have been proposed, such as 1) observation of water in concrete over time (imaging with permeating neutrons), 2) detection of defects (stagnant water and voids) inside concrete (reflection imaging with backscattered neutrons), and 3) nondestructive measurement of chloride amount in concrete (elemental analysis utilizing neutron capture prompt γ-rays). All these methods can be quantitative, and the distribution in the depth direction from the concrete surface can also be evaluated nondestructively from 2) and 3). As water affects the characteristics of concrete, and water and chloride affect the deterioration progress of concrete structures, neutron beams have the potential to be a means of providing important information related to the soundness of concrete structures.

Table 1: Committee Members

Chairman	Koichi Kobayashi (Gifu University)
Secretary	Toshie Otake (RIKEN) Manabu Kanematsu (Tokyo University of Science) Yoshimori Kubo (Kanazawa University) Shigeki Seko (Aichi Institute of Technology) Toshihiko Nagatani (Nippon Expressway Research Institute)
Committee Members	Go Igarashi (The University of Tokyo) Yukari Ishikawa (Chuken Consultants) Yoshinobu Oshima (Nakano Corporation) Kentaro Ono (Tokyo Metropolitan University) Shinichiro Okazaki (Kagawa University) Shuichi Ono (Japan Construction Machinery and Construction Association) Toshinori Kanemitsu (Central Research Institute of Electric Power Industry) Yuya Sakai (University of Tokyo) Masaki Suzuki (Takenaka Corporation) Takayoshi Tomii (Obayashi Corporation) Koichi Matsuzawa (Architectural Research Institute) Yuya Yoda (Shimizu Corporation) Ken Watanabe (Railway Technical Research Institute)
Advisor	Isao Ujiie (Ehime University)

Based on the above, the "FS Committee on Inspection and Assessment of Concrete Using Neutron Beams" was established in fiscal year 2018, and a one-year feasibility study was conducted on the utilization of neutron beams in the non-destructive investigation of concrete structures. As a result, the "Technical Committee on Inspection and Assessment of Concrete Using Neutron beams" conducted activities in fiscal years 2019 and 2020. **Table 1** shows the list of committee members.

2. Neutron Sources Available in the Concrete Engineering Field

X-rays are well-known as a method to image the inside of a concrete structure, and in recent years they have been utilized for investigating the non-filling of grout in the ducts of prestressed concrete (PC) cables, etc. X-rays are a type of electromagnetic wave, whereas neutron beams are classified as particle beams, which is a state in which neutron particles travel in bundles. Features of neutron beams are low permeability for hydrogen, lithium, boron, etc., and high permeability (ease of permeation) for silicon, calcium, oxygen, aluminum, iron, etc., which are the main components of cement and aggregate. In particular, water is involved in the majority of concrete degradation processes, but neutron beams differ from X-rays in that they can capture water directly.

Neutron sources that have been applied to concrete and concrete structures include the following:

(1) Nuclear reactors

This is where a neutron beam generated by a fission reaction in a nuclear reactor is extracted and utilized. Currently, there exist two nuclear reactors in Japan to be used for the industrial research: the JRR-3 operated by the Japan Atomic Energy Agency and the KUR operated by the Kyoto University Institute for Integrated Radiation and Nuclear Science.

(2) Particle accelerators

A particle beam (such as a proton beam or an electron beam) accelerated by a particle accelerator collides with a target to produce a nuclear reaction, thereby generating neutrons. A typical example of a large one is the J-PARC, which is a high-efficiency large-intensity neutron source that utilizes nuclear spallation reactions by high-acceleration energy. In contrast, the RANS of RIKEN, which was also used by this committee, utilizes low-energy nuclear reactions, and realizes the miniaturization of the entire apparatus, while with a lower generation efficiency.

Although acceleration energy differs by a factor of approximately 1000 in large and small devices, both are classified into this system as neutron generation methods. Recently, there have also been many new design plans of particle accelerator-type neutron sources for medical use.

(3) Radioisotopes

This is where neutrons generated by the spontaneous fission of ^{252}Cf are utilized. The previous two systems have neutron generation intensities several thousands to more than 0.1 million times higher than this system and are available as convergent beams, whereas this system is a scattering type radiation source with weak neutron intensities.

3. Utilization of Neutron Beams for Inspection and Assessment of Structures

3.1 Study policy

The types and precision of information obtained from these investigations vary according to the objective, such as inspections on quality control during the construction of concrete structures, investigations to evaluate the presence or absence of deformation of existing concrete structures, and investigations to classify structures based on the types of initial defects, damage, and degradation and to ascertain the deformation[1)]. In addition, the soundness shall be comprehensively evaluated by multiple combinations of such results, and additional investigations and necessary measures should be selected.

Therefore, an arrangement of the present state and problems of inspection and assessment toward applications using neutron beams in the inspection and assessment of structures was conducted. The current state of inspection and assessment at various organizations were investigated.

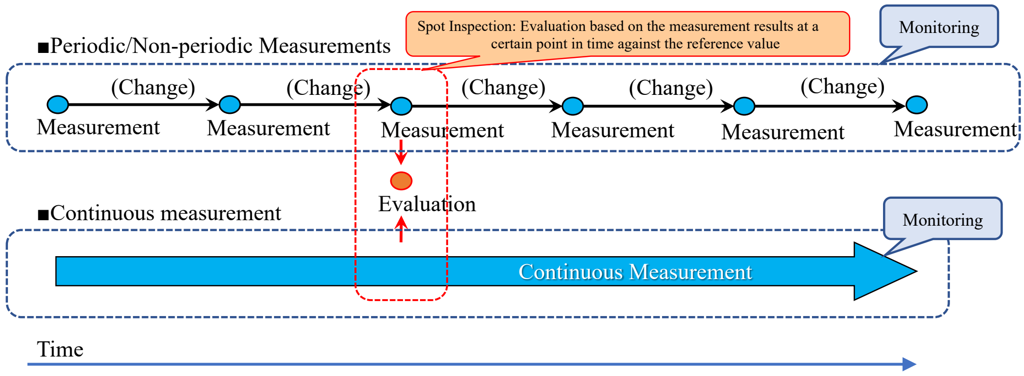
3.2 Objectives of inspection and assessment and required technologies

The purpose of inspection and assessment is ultimately to evaluate the soundness of the structure such as to take appropriate measures. In the case of bridges, it is necessary to take measures based on the soundness of each girder, and each bridge should be comprehensively evaluated from individual investigation results. Therefore, the results of nondestructive investigations must be connected with appropriate measures. For example, if no measures are prepared for a degradation (e.g., early corrosion of rebar), it may be judged as "sound" or "slight degradation " and left unattended; thus, the investigation results will be valuable only if there are effective measures for the degradation. Further, the accuracy of non-destructive investigations has improved, and even if a minute degradation can be detected, the significance of the accuracy improvement will also be attenuated unless appropriate measures are implemented. Particularly in the case of investigations aiming at preventive maintenance, effective preventive maintenance measures are necessary even in the initial stage of deterioration, as well as technologies for detecting slight degradation, and the significance of nondestructive investigation arises only when both are combined. However, the types of "countermeasures" are selected based on objective facts obtained from a "survey" and evaluated by the tacit knowledge of engineers. In general, nondestructive investigations have many technical problems in their application in the field, such as limitations of the area that can be investigated and difficulties in improving the accuracy. Therefore, the establishment of an evaluation method that combines the results by multiple investigation methods, the technological development of equipment to investigate multiple degradations with a single piece of equipment, and the technological development of techniques enabling the investigation of areas that previously could not be investigated by nondestructive investigation are considered as future research subjects.

The Study Committee for the Promotion of Monitoring Technology Utilization for Social Infrastructure (MLIT home page) indicates the direction of technological development[2)], and inspection, and monitoring are defined as shown in **Figure 1**[2)]. The expected roles for maintenance are classified according to each maintenance management stage at inspection, repair, maintenance, and emergency, requirements for monitoring technology and important matters to be adopted in on-site applications are arranged as shown in **Table 2**[2)].

In this committee, we performed investigations while adhering to such a course of action. As specific structures, we targeted PC structures, road bridge RC decks, port structures, electric power facility structures, agricultural water utilities, and buildings.

As a paper is insufficient for describing each structure in detail, the examination results for PC structures are herein presented as representative examples.



(Reference) Meanings in the *Kojien* Dictionary

Spot Inspection: To inspect one by one.

⇒ Inspection: To check for suitability, abnormality, and irregularity following a standard.

Monitoring: To observe, investigate, and analyze.

⇒ Observation: To observe and measure the transition and change of a natural phenomenon.

⇒ Investigation: To check to clarify certain matters.

⇒ Analysis: To disassemble an object and identify the components, elements, and characteristic aspects.

Fig. 1: Definitions of Inspection and Monitoring Techniques

Table 2: Requirements for Monitoring Technologies and for Field Applications [2)]

What is required	Requirements for field application
• Measurement items, locations, frequency, accuracy, and reliability according to the purpose • Equipment and systems such as sensors that match the measurement content, etc. • Cost, operability, and durability applicable to the site • Rational correlation between measurement data, etc., and deterioration, damage, repair, etc.	• What can be achieved at a cost commensurate with the achievement of reduction and leveling of total costs • Accuracy and reliability commensurate with the phenomena to be identified such as deterioration damage, etc. • Consistency in the level of technical knowledge such as deterioration mechanisms • Ability to maintain performance in various environments while in service • Capability to maintain performance for a period commensurate with the life of the structure and the inspection cycle • Ability to efficiently collect, organize, and analyze large volumes of measurement data for use in maintenance and management • Installation and data acquisition shall be possible even after the start of construction and operation.

3.3 Applicability to Maintenance of PC Structures

In this study, the current issues in the inspection and assessment of PC structures in relation to deterioration and performance are summarized. Regarding the degradation of PC structures, inspection and extraction of survey points were conducted, particularly focusing on factors related to corrosion and rupture of PC tendons, and the application scope of neutron beam utilization by imaging scenarios of maintenance and management was examined.

Figure 2 shows a conceptual diagram of degradation degree and performance degradation in PC structures. In PC structures, the concept of performance degradation as a PC girder is associated in inspection and assessment to the degree of deterioration progress. In contrast, a characteristic of the load carrying performance of PC girders is that, in the relation between load and deflection relative to bending action, there is less allowance of load carrying capacity from crack generation to fracture in comparison with RC girders. Therefore, in PC structures, it is important to perform inspection, investigation, and assessment for deterioration that cause corrosion and rupture of PC steel, which is a major factor of performance degradation.

Maintenance in PC structures is divided into preventive maintenance, in which deterioration precursors are identified and measures are taken before deterioration occurs, and corrective maintenance, in which deterioration conditions confirmed by inspection are evaluated based on related technical standards, and repair and reinforcement are conducted as necessary. The deterioration state according to the inspection is judged by the existence of deflection and pavement pot holes on road surfaces, caused by slab upper surface deterioration, in addition to crack generation, presence of water leakage, and delamination and spalling of concrete due to steel corrosion, etc.

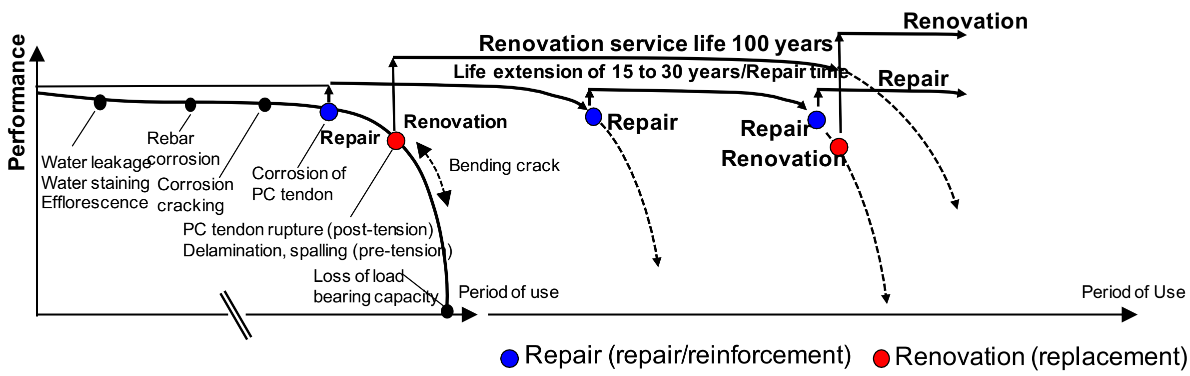


Fig. 2: Conceptual Diagram of PC Structure Maintenance Scenario

In this committee, we studied the applicability of the non-destructive test by neutron beam, assuming the service ages of PC structures. In the performance degradation curves shown in **Figure 2**, two scenarios are shown: a preventive maintenance plan in which life is prolonged by repair and reinforcement, and a corrective maintenance plan in which renovation is conducted before the end of service life. Therefore, during the utilization and maintenance period, inspection, survey and assessment, soundness evaluation, countermeasure design, repair and strengthening, and renovation are conducted. In addition, investigation items associated with soundness evaluation and countermeasure examination are extracted by existing nondestructive inspection methods, such as inspection, survey, and judgment items in which neutron beams can be utilized. Thus, we compared these methods.

3.4 Applicability of PC structures to non-destructive inspection and diagnostic technology

To examine the utilization policies (action plans) of inspection and assessment using neutron beams, the defects in which the utilization of neutron beams is expected in ascertaining the deformation of PC structures and the nondestructive inspection methods aimed to be utilized for each degradation factor were investigated, as well as the latest information on present nondestructive inspection technologies.

(1) Defect

Water was mainly involved as the transformation factor, and in some cases, degradation factors other than water were also introduced into the PC structures. **Figure 3** shows the layout of PC steel and water leakage routes for a PC box girder.

For example, a case of rupture of PC tendon by corrosion related to water penetration in precast PC girders is described below. The precast PC girder is of a type in which a I-shaped girder or T-shaped girder is set up by truck crane, etc., with span length of approximately 20–40 m after being manufactured near the bridge site or at the factory. The PC tendon of the PC girder is fixed at the end of the girder in the case of a span of approximately 20 m, but in cases where the span exceeds 40 m, some were fixed on the upper edge on the main girder, such that water penetrates into PC steel from the anchorage part due to water leakage from the slab joint at the end of the girder. In addition, as water from the road surface also infiltrates the upper anchorage part, the PC tendon corrodes and ruptures due to the penetration of water containing de-icing salt.

(2) Deterioration factors and nondestructive inspection methods

Regarding the infiltration of "water" (improper filling of PC grout), water may infiltrate into steel sheaths where filling of grout is insufficient from the pavement by road surface drainage, and from the PC tendon anchors due to water penetration from the slab joint, after which corrosion of PC tendon may develop, leading to rupture.

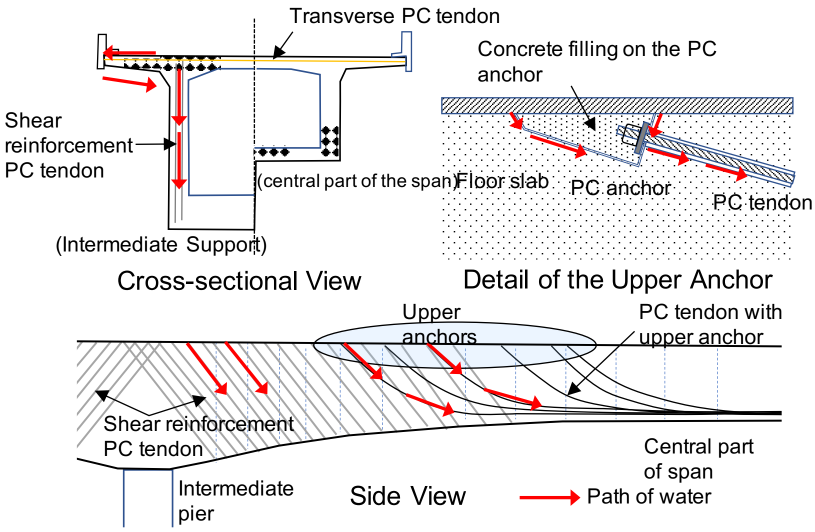


Fig. 3: Arrangement of PC Steel and Water Leakage Pathways of PC Box Girder

Standing water on bridge surfaces and malfunction of the drainage equipment, etc., may cause degradation due to water leakage from road shoulders. In addition, "water" penetrates from construction joints and cracks, etc. Concrete delamination, rebar exposure, rust stain, etc., result in further deterioration due to the penetration of "water". In road bridges, etc., the effect of the infiltration of "water" containing de-icing salt is large. Therefore, utilization of nondestructive inspection to ascertain the water infiltration route is desired.

Regarding "chlorides", degradation by chloride attack and frost damage scaling may occur at bridge with considerable airborne salt near coasts or in road bridges where a large amount of de-icing salt is used in winter. As corrosion of steel is a concern when the chloride quantity in concrete exceeds the corrosion threshold limit, utilization of nondestructive inspection methods capable of quantitative evaluation of chloride amount in concrete are desired.

Regarding "corrosion and rupture of PC steel", when corrosion of PC steel progresses, the PC steel ruptures, and the decrease of effective prestress may lead to reduction of the load carrying performance of bridges. Therefore, when the possibility of breakage of PC steel is considered, it is necessary to estimate the residual prestress, check the load carrying performance, and confirm the safety. Therefore, the utilization of nondestructive inspection technology specified on the rupture of PC steel is desired.

(3) Non-destructive investigation technologies

Regarding nondestructive inspection technologies for PC structures such as radiography, percussive vibration method, broadband ultrasound method, impact echo method, SIBIE method, coring method, and leakage magnetic flux method, the inspection objectives (targets), principles, and application ranges were considered.

As a typical example, this paper presented only partial examination results for PC structures, and the same examination was conducted for other structures.

4. Testing and Surveying Technologies Using Neutron Beams

A summary of cases based on the preceding literature, in which various tests and investigations were conducted using neutron beams, is presented. The measurement object fields considered are 1) defect exploration, 2) unit water quantity measurement, 3) stress measurement, 4) water transport measurement, 5) chloride ions, 6) cement materials, 7) soil and porous concrete, and 8) others.

4.1 Defect exploration

Research has been performed aimed at detecting voids, etc., in concrete structures capable of utilizing the characteristics of neutron beams when trying to detect the defects in concrete. Neutron beams have material permeability and show scattering and energy attenuation by collision with light elements. Therefore, the main objects of exploration are voids in structures, in which it is difficult to directly investigate the defects inside, such as in steel and concrete composite structures, or the delamination and voids, etc., that occur between asphalt pavement and concrete slabs, etc.

Inspection technologies by mainly two methods have been studied in Japan. One is a scattering type measurement system that uses a radioisotope (RI) neutron source to measure thermal neutrons that are scattered and attenuated when irradiated on a measurement target. The other is an instrument that uses a particle accelerator as a neutron source to irradiate neutrons to a measurement target at almost regular intervals and measures the fast neutrons that penetrate the target or the neutrons that rebound after being scattered or attenuated.

4.2 Estimation of unit water mass of fresh concrete

An estimation technique of unit water mass in fresh concrete using neutron scattering was proposed by Lepper in 1972[3)], after which having been improved, and more active examinations have been conducted in Japan since the latter half of the 1980's. Californium and cobalt-60 were the majority of radiation sources, and many studies have been conducted at laboratory and field levels.

Consequently, COARA continuous-type RI-concrete unit water mass analyzers have been rented and marketed in the Japanese market. The radiation source is ^{252}Cf, and the equipment and the data acquisition are operated by a wireless system. In addition, the product based on the past research is generally marketed as the Aqua Monitor. Outside Japan, evaluations seem to be generally performed with the 4430 Water-Cement Gauge sold by Troxler Electronic Laboratories.

4.3 Stress measurement

RC is a composite material that combines compression-resistant concrete and tension-resistant steel rebar. These relationships change according to the bond characteristics of the rebar and the concrete, and the characteristics of RC members considerably change due to cracks in the concrete and corrosion of the rebar, etc. Generally, rebar stress is measured by a gauge affixed to the surface of the rebar. However, as the effect of waterproofing of the gauge parts, and of wiring, etc., on the adhesion characteristics with the concrete cannot be neglected, treatments to reduce the effect on measurement are often performed, such as cutting grooves on the surface of the rebar or attaching gauges by drilling holes in the rebar. However, in measurement using gauges, measurement points for attachments become discrete, and measurements adjacent to cracks, and application to corroded rebar, etc., become difficult.

Measurement by the neutron diffraction (ND) method using neutron beams has been proposed as a technique to solve these problems. The ND method is a strain measurement method in which the distance between atoms is treated as the gauge point distance, and it is the only method in which stress and strain in the deep parts of a material can be measured nondestructively and without contact. Therefore, this is a very effective technique that can evaluate the stress state of rebar inside concrete, and research results have been published since around 2008. Stress measurement by the ND method started from "Deployment of neutron utilization technology to the architectural field" of the Youth Special Research Committee of the Architectural Institute of Japan (Chief: Prof. M. Kanematsu).

In rebar stress measurement, the rebar is placed inside the concrete, and examinations on the applicability of the ND method have been conducted. In addition, examinations on the stress changes of the rebar around the crack have also been conducted when cracking occurs on the concrete surface. In bond stress measurement, tensile test of reinforced concrete specimens has been conducted, the bond stress distribution is measured in tandem with loading tests of the beam specimens, and verification of the truss and arch theory by the ND method has been attempted. In stress measurement of post-installed construction anchors, examinations have been conducted on the bond stress distribution of several types of anchors by the ND method. The effect of cyclic loading on the change of bond stress is also discussed. Regarding bond stresses in corrosion cracks, as well as during repairs, the ND method has been used to measure bond stress distribution when the rebar inside the concrete is corroded; furthermore, verification on recovery of bond stresses has also been performed by measuring bond stresses after filling in cracks generated due to rebar corrosion with repair material.

4.4 Water transport measurement

Neutron imaging is a technique that can be called “X-ray radiography of a neutron beam”. As the interaction between neutrons and hydrogen is brisk, the measurement sensitivity to moisture is high, and the measurement of water transport in concrete has been actively applied. In particular, it enables the observation of the water behavior with good sensitivity by measuring differential images between any desired times. This technique has often been applied to water transport in hardened concrete, water transport in cracks, etc. As the temperature dependence in the measurement technique is small, it is also used for observation of water behavior under high temperature, etc. The spatial resolution is approximately 0.1 μm/pixel at the maximum, and the specimen thickness is approximately 10 cm at the maximum, depending on the radiation source. Although the time resolution is usually a few seconds to a few minutes, it is possible to increase the resolution to a few milliseconds per image by using a neutron imaging intensifier.

In 2004, Yatsuyanagi et al. [4)] and Kawabata et al. [5)] succeeded in observing concrete using KUR (Kyoto University Institute for Integrated Radiation and Nuclear Science), to visualize the difference in moisture status according to curing conditions. In addition to KUR, examinations have also been performed in Japan using JRR-3 (Atomic Energy Agency Research Reactor) and the RANS of RIKEN. In recent years, the number of reports on water transport observation using neutron imaging has increased because of interest in water penetration phenomena, partly due to the fact that water penetration has been considered in the reinforcement corrosion in Standard Specifications for Concrete Structures [Design] of the Japan Society of Civil Engineers enacted in 2017, and due to the fact that testing methods for the penetration rate of water penetrating into concrete have been established in the standard "Test method for water penetration rate coefficient of concrete subjected to water in short term" (Draft) (JSCE-G 582-2018) of the Japan Society of Civil Engineers.

4.5 Chloride ion measurement

When neutron beams are irradiated on a material, prompt gamma rays, a type of radiation, are immediately emitted. As prompt gamma-rays have an energy specific to the atomic nucleus, the type of an element and the quantity of a substance can be determined by detecting and analyzing these. This technique is called prompt gamma-ray analysis (PGA: neutron-induced prompt gamma-ray analysis), and in the concrete field, it is applied to nondestructive measurement of the distribution of chloride ions in concrete in the depth-wise direction by utilizing the high penetrability of neutron beams.

Regarding applicability of chloride ion measurement by PGA to concrete, measurement techniques using RIs have been examined in foreign countries since around 2000. In Japan, research using nuclear reactors has been conducted since around 2007, and it has been shown that perfect nondestructive measurement of chloride ions in concrete is possible. In recent years, PGA using a particle accelerator has been developed, and measurement of chloride ion distribution in the depth-wise direction and determination of chloride ion quantities of concrete in which admixtures have been used have become possible.

Inspection technology by mainly two methods has been studied in Japan. One is a technique that measures PGA by using the neutron source of a reactor (JRR-3). The other is a technique that measures PGA generated by accelerating protons using a particle accelerator (RANS). In foreign countries, there are reports on measurement techniques with a particle accelerator (KFUPM) and measurement techniques using RIs.

4.6 Evaluation of cementitious materials

The quasi-elastic neutron scattering (QENS) method, which is one of the neutron scattering methods, can acquire the progress of hydration reactions over time while remaining non-destructive, and can identify the state distribution of water such as free water, bound water, and gel water in the microstructure. QENS method can also be utilized for the observation of the formation process of ice in the microstructure. ND has been used for the observation of changes in the growth of hydrate phases over time. The small angle neutron scattering method (SANS) has been confirmed to be suitable for characterization of microstructures. SANS is used to observe changes in the fractal dimensions of the surface and volume of C-S-H gels over time and the effects of admixtures such as fly ash and silica fume. In addition, SANS has also been applied to the characterization of aggregates, where the Alkali Silica Reaction should be avoided. Combining these neutron scattering methods can enable applications to specific problems, and also new interpretations of the microstructures of Portland cement pastes.

4.7 Soil and porous concrete

The moisture content in soil can be obtained from the count ratio. Compared with other soil moisture measurement methods, measurement is possible in a short time, as well as monitoring in real time. In addition, repeating a measurement in the same location is also possible because the measurement is non-destructive. As the measured water content values are not affected by geological conditions, particle size distribution, structure of pores, etc., the number of experiments for calibration can be reduced. This has already become a technology at the field level, and has been applied to measure the water content near the ground surface and also to the measurement of water content around boreholes and drainage tunnels, etc.

Using a similar apparatus, the porosity of porous concrete in a fresh state has also been measured. The equipment is portable, and it has also been confirmed in previous studies that it has sufficient accuracy, with a practical level.

4.8 Other

Covault et al. estimated Portland cement content in mortar specimens using a Van der Graff accelerator, aiming at the estimation of the unit cement mass in concrete[6)]. Using various specimens, the integrated value of the 3.07-mev peak corresponding to the ^{49}Ca excited by thermal neutrons and the calibration curve were prepared, and testing was conducted on the mortar specimens, resulting in a 95% confidence interval of approximately 0.7 g/g mortar for the estimated cement quantity, which indicated that evaluation with high-precision was feasible.

Okazaki et al. estimated the “local” mix proportion in a cylindrical concrete specimen using a prompt gamma-ray analyzer installed in a research reactor with the aim of non-destructively estimating the mix proportion of the concrete[7)]. Using test specimens of various water/cement ratios and aggregate amounts, they calculated the unit cement mass from the amount of Ca that corresponds to 1942 keV, similarly as in reference 6). In addition, the unit aggregate mass was estimated by subtracting the amount of silicon derived from the cement from the total spectral value for silicon that corresponds to 3540 keV. By assuming the air quantity to be 5%, the unit water mass can be estimated, and as the unit mass of all constituent materials are required, the water/cement ratio can also be evaluated.

5. Development of a Neutron Source Capable of Inspecting and Diagnosing Actual Structures

In 2013, a cooperative team consisting of RIKEN and the Tokyo Institute of Technology developed the small neutron source system RANS with the aim of using it for inspection and assessment of concrete structures, and research utilizing it has been conducted. In 2019, the further-miniaturized RANS-II was developed. These are referred to as “small” here, but this means smaller compared with ordinary accelerators. In the case of RANS, the main body of the accelerator weighs 5 tons, and the total length of the device is 15 m. Compared to this, RANS-II is more compact and can be mounted on vehicles to move to the target structure. An outline of both is shown in **Table 3**.

Table 3: Outline of RANS and RANS-II [8)]

	RANS	RANS-II
Accelerated ions	Hydrogen (proton)	Hydrogen (proton)
Energy	7 MeV	2.49 MeV
Maximum ion current	100 μA	100 μA
Neutron-generating nuclear reaction	$^{9}Be(p,n)\,^{9}B$	$^{7}Li(p,n)\,^{7}Be$
Maximum neutron energy	5 MeV	0.7 MeV
Accelerator system	Connects two accelerators	One only
Accelerator weight	5 tons	2.5 tons
Shield weight	20 tons	3 tons
Equipment length	15 m	5 m

As previously described in Sections 4.4 and 4.5, study results have been obtained on the measurement of water distribution and transport conditions in concrete and chloride distribution.

In addition, the RANS-III has been developed on the assumption that inspection of the actual structure will be performed by actually mounting the device on truck, and when operated, the possibilities of inspecting and diagnosing the concrete structure by neutron beams are expected to dramatically expand.

6. Potential Applications for Neutron Beam Inspection and Diagnostics

This committee has indicated the present state of the technology of nondestructive testing of concrete by neutron beams and the development of the technology in the near future, after identifying the needs of investigation and inspection on structures and buildings, and has examined the possibility of investigation and inspection of structures and buildings utilizing small mobile neutron sources.

Neutron reflectance imaging can be used, for example, to defect, graveling, lining thickness measurement, and back cavities at the sides of the web and bottom flange of PC girders, RC slabs of road bridges, the bottom of pier superstructures, and the sides of caissons, and can investigate the state of joint interfaces and the interfaces between bonded steel plates and base metal, as neutron beam can penetrate up to approximately 300 mm from the concrete surface. In addition, the possibility of three-dimensionally visualizing the state of crack direction and dispersion in the depth-wise direction from the surface is conceivable. If water leaks at electric power facilities such as dams or agricultural water utilities, the routes and ranges can be identified. Furthermore, as the chloride in concrete can be evaluated from 0.3 kg/m^3, neutron beams have considerable potential as a non-destructive inspection technique for concrete structures, such as non-destructive depth-wise measurements of the chloride distribution not only in structures in marine environments, but also in structures affected by de-icing salt. Therefore, when a portable neutron source system, as introduced in Section 5, is put into operation, it is expected to be a powerful tool for investigating and inspecting new structures.

This report has introduced some of the results of the committee. For details, refer to the committee report released in September, 2021.

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