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Dynamic Material Testing of Aged Concrete Cores From the Outer Wall of the High-Flux Advanced Neutron Application Reactor

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Concrete structures must maintain their shielding abilities and structural integrity over extended operational periods. Despite the widespread use of dry storage systems for spent nuclear fuel, research on the properties of deteriorated concrete and their impact on structural performance remains limited. To address this significant research gap, static and dynamic material testing was conducted on concrete specimens carefully extracted from the outer wall of the High-flux Advanced Neutron Application ReactOr (HANARO), constructed approximately 30 years ago. Despite its age, the results reveal that the concrete maintains its structural integrity impressively well, with static compression tests indicating an average compressive strength exceeding the original design standards. Further dynamic property testing using advanced high-speed material test equipment supported these findings, showing the consistency of dynamic increase factors with those reported in previous studies. These results highlight the importance of monitoring and assessing concrete structures in nuclear facilities for long-term safety and reliability.

Keywords: Dry storage system, Concrete structures, Deterioration, Dynamic material properties

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1. Introduction

Among the dry storage systems for spent nuclear fuel, all systems except the metal cask system include a canister for the containment boundary and a concrete overpack for shielding and protection from the external environment. Concrete structures in spent nuclear fuel (SNF) interim storage facilities must maintain their shielding ability and structural integrity under normal, off-normal, and accidental conditions. Dry storage systems for SNF have been in use for more than 20 years, and the period of use is expected to further increase.

Therefore, concrete structures may deteriorate if an interim storage facility operates for several decades. Even in the event of deterioration, it is crucial for concrete structures to retain their functions, such as radiation shielding and structural integrity. Therefore, establishing an analysis methodology capable of evaluating whether deteriorated concrete structures maintain their integrity under normal or off-normal conditions and during accidents is necessary.

Research on the deterioration of concrete in radioactive waste facilities, such as dry storage facilities, has been consistently performed [1-3]. However, studies on the properties of deteriorated concrete have not yet been conducted. To confirm whether the deteriorated concrete structure maintains its shielding function and structural integrity, its material properties must be determined and included in the analysis model. Therefore, we investigated the deterioration mode of dry storage systems, fabricated surrogate degradation specimens to measure the static and dynamic properties of deteriorated concrete, and developed an analysis model that incorporates these degradation effects.

Most structural materials are sensitive to the loading rate [4]. Particularly, the concrete strength is greatly affected by the strain rate. Moreover, concrete structures are affected by high strain rates from different sources, such as natural hazards or industrial accidents [5]. Loading rates can range from the static case of $10^{-5}\cdot s^{-1}$, through an intermediate range (10^{-1} to $10^{-5}\cdot s^{-1}$) that requires the consideration of inertial forces, to much higher levels (approximately $10\cdot s^{-1}$) that encompass either impact or explosive loading [4].

In concrete-related codes, a dynamic increase factor is introduced to consider changes in the mechanical properties according to the strain rate. The dynamic increase factor (DIF) represents the ratio of dynamic strength to static strength and is reported as a function of the strain rate. In ACI-349 [6], only the strain rate is used as a variable in the empirical formula obtained from the test results of the specified concrete strengths of 28–42 MPa. The maximum value of the DIF is limited to 1.25 in the axial direction and 1.10 in the shear direction. However, in the CEB (Euro-International Committee for Concrete) model [6], the static strength is included as a variable in addition to the strain rate, and a constitutive equation in which the slope changes from a strain rate of $30\cdot s^{-1}$ has been proposed.

In this study, a deterioration evaluation of the concrete in an old nuclear facility was performed. High-Flux Advanced Neutron Application Reactor (HANARO) was constructed at the Korea Atomic Energy Research Institute in 1995 following strict nuclear quality assurance standards. Because it has been approximately 30 years since it was built, some deterioration of the concrete wall was expected. Static and dynamic material testing were conducted on concrete cores extracted from the exterior wall of HANARO during seismic retrofitting [7].

2. Self-Disposal of Concrete Cores From HANARO

A material physical property test was conducted on the concrete core waste generated during the seismic retrofitting of HANARO [7].

Given that the distance to the HANARO reactor is of the order of several tens of meters, the likelihood that radioactive materials will attach to the wall is considered to be almost negligible. Moreover, the exposed dose was very low, so it is believed that activation did not occur. Although the outer wall of HANARO was barely exposed to radiation, the concrete cores were classified as radioactive waste because they were extracted and stored in radiation-controlled areas. Therefore, self-disposal must be performed to conduct material testing on extracted concrete cores.

The dimensions and radiation doses were measured, nuclide analysis was performed, and a self-disposal plan was submitted on November 24, 2022 [8]. The final approval was received from the Korea Institute of Nuclear Safety and Technology on April 25, 2023, and self-disposal (recycling) was completed in May of the same year [8].

The latest structural safety assessment of the outer wall of HANARO indicates that its non-destructive strength surpasses its design strength. However, the mechanical properties of concrete can be measured more accurately from destructive tests than from nondestructive tests.

Fig. 1. Specimens for dynamic material testing.

In this study, in addition to the static properties, the

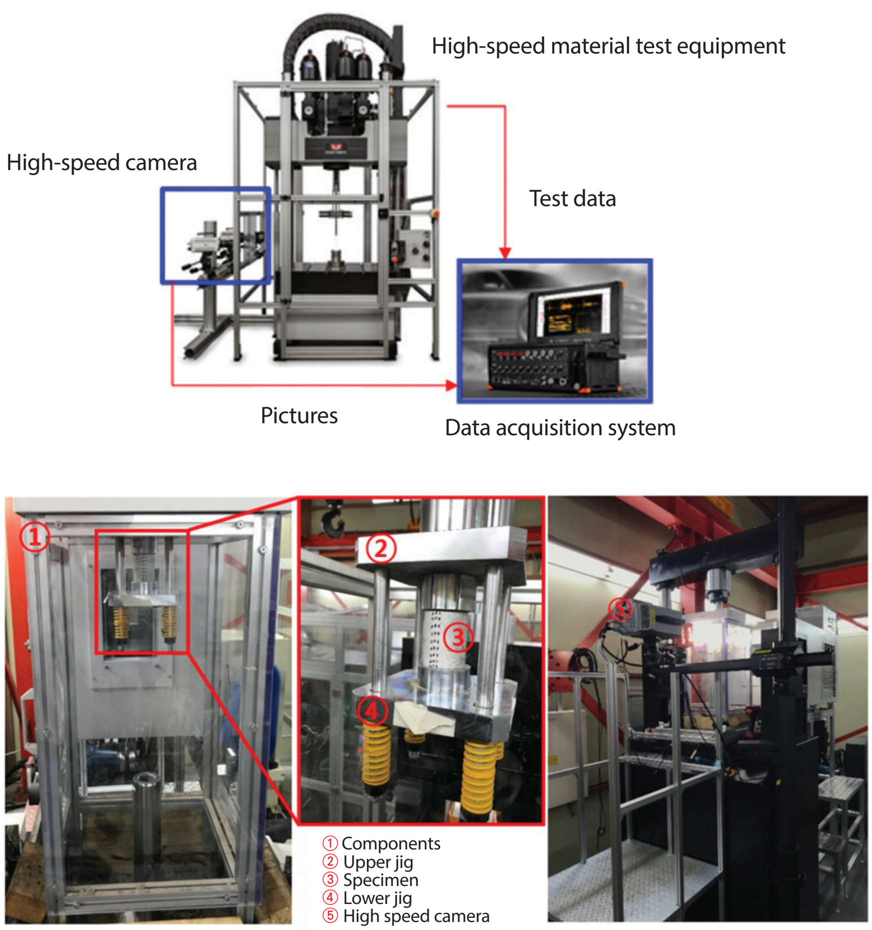

Fig. 2. High-speed material test equipment.

dynamic properties were measured to confirm whether the concrete of old nuclear facilities maintained its structural integrity.

3. Preparation for Material Testing of Concrete Cores From HANARO

3.1 Specimens for Static and Dynamic Material Testing

Specimens for the static tests with a diameter of 100 mm and a length of 200 mm were produced by waterjet cutting.

The shape of the specimen for concrete dynamic property testing was determined to exhibit uniform stress and strain distributions and represented the successful failure shape indicated in ASTM C39 through finite element analysis [9]. The dimensions of the specimen were determined through parametric studies of the height of the specimen and the presence or absence of a hole in the center of the specimen through finite element analysis. The final specimen shape had an outer diameter of 40 mm, an inner hole diameter of 5 mm, and a length of 50 mm [9].

Before conducting dynamic physical property tests, the specimens were processed using the waterjet cutting method, and their surfaces were polished and smoothed. Fig. 1 illustrates the manufactured specimens.

3.2 Test Equipment for Dynamic Material Testing

Dynamic material testing was carried out using a high-speed material test equipment established at the Korea Atomic Energy Research Institute, as shown in Fig. 2 [10]. It was designed and manufactured to perform high-speed tensile and compression tests at intermediate strain rates. A high-speed camera (Photron SA-Z) and a data acquisition system (DWEWSOFT R8DB) were used. The capacity of the test equipment was approximately 50 kN, and the operating speed was 6 m·s^{-1} [10]. Fig. 3 shows the concrete damage during dynamic material testing.

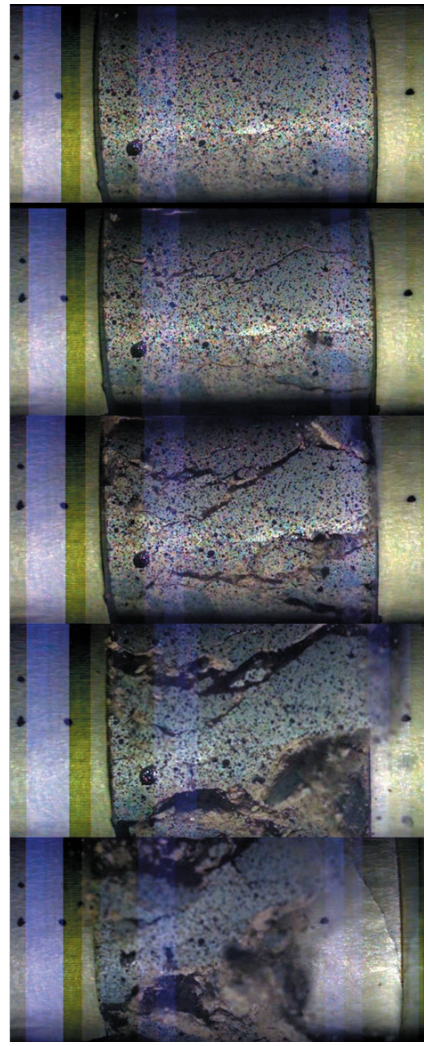

Fig. 3. Concrete damage during dynamic material testing.

4. Results

The results of the static and high-speed compression tests on the HANARO concrete specimens are shown in Fig. 4. The stress was obtained by dividing the load measured in the load cell by the specimen area, and the strain

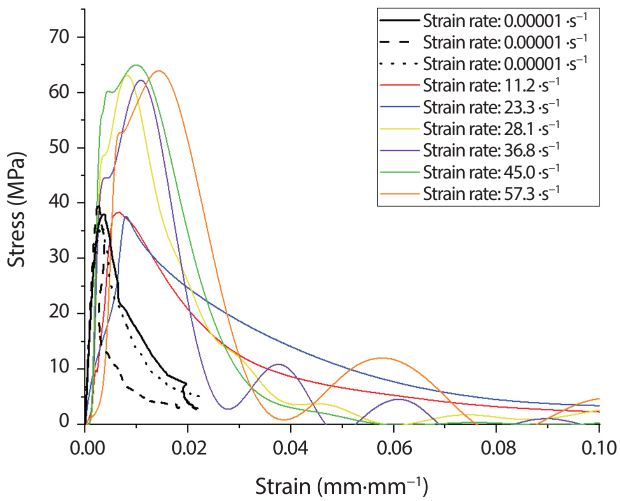

Fig. 4. Stress–strain curves of concrete cores from HANARO with respect to strain rate.

Table 1. Static compression test results of concrete cores from HANARO

No.	Peak stress (MPa)	Peak strain
1	37.96	0.0035
2	40.17	0.0033
3	35.84	0.0032

Table 2. Dynamic material testing results of concrete cores from HANARO

No.	Strain rate ($\cdot s^{-1}$)	Peak stress (MPa)	Peak strain	Dynamic increase factor (DIF)
1	11.2	38.4	0.0065	1.01
2	22.3	44.2	0.0052	1.16
3	28.1	63.1	0.0082	1.66
4	36.8	62.2	0.0110	1.64
5	45.0	65.0	0.0101	1.71
6	57.3	64.0	0.0142	1.68

was determined by analyzing the images captured with a high-speed camera. OMG's GOM Correlate software was utilized to analyze high-speed camera images [11].

We derived a stress–strain diagram where the stress is plotted on the Y-axis and the strain on the X-axis, as shown in Fig. 4. The tests were performed at six strain rates. The maximum compressive stress increased as the strain rate increased, owing to the speed dependence of the material.

Table 1 lists the results of the static compression tests. These results show that the average compressive strength is approximately 38 MPa, which was greater than the design strength and the average compressive strength for 28 d at the time of construction.

The dynamic property test results are listed in Table 2. The DIF, calculated as the ratio of dynamic strength to static strength using the static strength data obtained from the static test, is presented in the final column of Table 2. DIF values ranged from 1.01 to 1.71. Considering the strain rate of the present dynamic material test, the obtained DIF values were similar to those reported in previous studies (ranging from 0.9 to 1.8) [5]. The maximum stress and maximum strain increased in the dynamic test compared to that of the static test. This trend has also been observed in previous studies [4]. During rapid loading the slope has been observed to remain linear up to higher stress level, indicating a delay in the internal cracking process [4].

Based on the results obtained from the static and dynamic material testing of concrete cores from HANARO, which was built 30 years ago, the degree of concrete deterioration was concluded to be not significant in comparison with the static and dynamic results as well as the compressive strength at the beginning of construction. The similarity of the DIF value to those reported in existing references suggests that the concrete maintains its resistance to impact loads, indicating no significant deterioration.

5. Conclusions

We conducted static and dynamic material testing on concrete specimens extracted from the outer wall of HANARO, a nuclear facility constructed approximately 30 years ago. Static compression tests revealed an average compressive strength of approximately 38 MPa, surpassing the design and average compressive strengths at the time of construction. Dynamic property testing indicated that DIF values ranged from 1.01 to 1.71, values that were similar to those reported in previous studies that considered the strain rate. The results showed that despite its age, the deterioration of the concrete was not significant compared with its initial compressive strength. In the future, material property tests will be conducted on specimens simulating deterioration.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

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REFERENCES

[1] K. Kwon, H. Jung, and J.W. Park, “Service-Life Prediction of Reinforced Concrete Structures in Subsurface Environment”, J. Nucl. Fuel Cycle Waste Technol., 14(1), 11-19 (2016).

[2] K.I. Jung, J.H. Bang, J.B. Park, and J.H. Yoon, “Concrete Degradation Comparison of Computer Programs for Post-Closure Safety Assessment of Wolsong Low- and Intermediate-Level Radioactive Waste Disposal Facility”, J. Nucl. Fuel Cycle Waste Technol., 11(4), 311-324 (2013).

[3] J.S. Kim, D. Kook, J.W. Choi, and G.Y. Kim, “State-of-Arts of Primary Concrete Degradation Behaviors due to High Temperature and Radiation in Spent Fuel Dry Storage”, J. Nucl. Fuel Cycle Waste Technol., 16(2), 243-260 (2018).

[4] P.H. Bischoff and S.H. Perry, “Compressive Behaviour of Concrete at High Strain Rates”, Mater. Struct., 24(6), 425-450 (1991).

[5] M. Pająk, “The Influence of the Strain Rate on the Strength of Concrete Taking Into Account the Experimental Techniques”, Archit. Civil Eng. Environ., 4(3), 77-86 (2011).

[6] H. Kim, G. Kim, S. Lee, M. Son, G. Choe, and J. Nam, “Strain Rate Effects on the Compressive and Tensile Behavior of Bundle-type Polyamide Fiber-reinforced Cementitious Composites”, Compos. B. Eng., 160, 50-65 (2019).

[7] H.J. An, W.H. In, H.Y. Choi, K.H. Lim, S.O. Hur, S.H. Lee, and T.H. Kim. Status of Solid Radioactive Waste Generation in HANARO Seismic Retrofitting Construction, Korea Atomic Energy Research Institute Report, KAERI/TR-6967/2017 (2017).

[8] J.H. Lim, Y.J. Hong, S.H. Lee, and S.S. Cho. Year-2022 Self-Disposal of Concrete Cores From HANARO for Material Testing, Korea Atomic Energy Research Institute Report, KAERI/TR-9257/2022 (2022).

[9] J. Lee and S.S. Cho, “Novel Concrete Specimen Geometry for Dynamic Compression Tests”, JMST Adv., 6(1), 75-87 (2024).

[10] Y.Y. Yang, J.M. Lim, J.W. Lee, and S.S. Cho. A Construction Report of Intermediate High Speed Material Test Equipment, Korea Atomic Energy Research Institute Report, KAERI/TR-9265/2022 (2022).

[11] GOM Metrology. “Digital Image Correlation: Motion and Deformation Analysis.” GOM homepage. Accessed Sep. 28 2023. Available from: https://www.gom.com/en/topics/digital-image-correlation.