

Development and Validation Plan for Dynamic Material Models of Degraded Concrete in Dry Storage Systems

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1. Introduction

Concrete structures in spent nuclear fuel interim storage facilities must maintain their shielding capability and structural integrity under normal, off-normal, and accident conditions. If an interim storage facility operates for several decades, the concrete structures may deteriorate. However, even in the presence of deterioration, these structures must continue to fulfill their essential functions, such as radiation shielding and structural integrity.

Therefore, it is necessary to establish an analytical methodology to evaluate whether a deteriorated concrete structure maintains its integrity under not only normal and off-normal conditions but also accident conditions. In this study, a concrete dynamic material model for dry storage facilities was developed and the developed dynamic material model will be validated using the data of additional testing.

2. Development of Concrete Dynamic Material Model for Dry-Cask Storage System

Currently, the concrete used in domestic dry storage systems has no designated safety grade, so it follows the KEPIC SGB standard for structural concrete, which adopts ACI 318 for mix design. In this project, the Korea University research team designed Mix-1 accordingly and produced test specimens. They also developed Mix-2 and Mix-3 and conducted tests with those specimens. In the freeze-thaw and thermal degradation tests conducted in this study, specimens made using Mix-1-Batch Plant were used.

Table 1. Concrete mix design for dynamic material testing

	W/B	G m a x [mm]	S / a [%]	W [kg]	C [kg]
Mix 1-Batch Plant	0.42	19	47.4	148	344
Mix 1-Lab. (KU)	0.42	19	47.4	148	344
Mix 2-Lab. (KU)	0.38	19	44.27	157	330.5
	FA [kg]	Sand [kg]	Gravel [kg]	SP [kg]	AE [kg]
Mix 1-Batch Plant	0	869.79	965.21	0.60%	0.40%
Mix 1-Lab. (KU)	0	869.79	965.21	0.60%	0.40%
Mix 2-Lab. (KU)	82.625	769.43	968.77	0.60%	0.30%

The dynamic material testing was conducted using intermediate high speed material test equipment installed in KAERI in 2022.

2.1 Non-degraded concrete

Figure 1 presents the dynamic material testing results for non-degraded concrete and the concrete from HANARO, a 30-year-old nuclear facility. It was confirmed that the HANARO concrete maintains sufficient strength, and a regression equation for the non-degraded concrete was developed based on the test data.

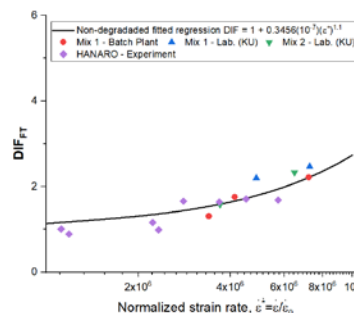


Fig. 1. Regression equation for DIF of Non-degraded concrete

2.2 Freeze-thaw deteriorated concrete

The results of dynamic material testing performed on specimens subjected to freeze-thaw cycles and those exposed to both freeze-thaw and salt attack showed little difference among the test parameters. The difference between the specimens exposed only to freeze-thaw cycles and those exposed to both freeze-thaw and salt attack was negligible, and the variation with the number of freeze-thaw cycles was also minor.

It is considered that freeze-thaw deterioration had sufficiently progressed after 100 cycles, resulting in little additional degradation beyond this point. Therefore, it is necessary to conduct further tests on specimens subjected to fewer than 100 freeze-thaw cycles. The dynamic increase factor (DIF) and strain at the point of maximum stress obtained from the freeze-thaw tests were compared with those of non-degraded concrete.

Since the DIF is defined as the ratio of the dynamic compressive strength to the static compressive strength, it is influenced not only by the dynamic strength but also by the static strength. For the specimens subjected

to freeze–thaw cycles, the DIF was found to be smaller than that of non-degraded concrete at strain rates exceeding 50/s. In contrast, the strain corresponding to the maximum stress was observed to increase compared to that of non-degraded concrete.

Overall, as the specimens weakened due to degradation, the strain at maximum stress tended to increase while the maximum stress itself decreased. Based on these findings, regression equations were developed to estimate the dynamic increase factor and the strain at maximum stress for freeze–thaw–deteriorated concrete.

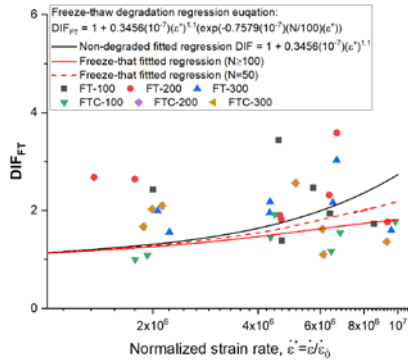


Fig. 2. Regression equation for DIF of freeze-thaw degraded concrete

2.3 Thermal deteriorated concrete

For concrete subjected to thermal degradation, the DIF was found to decrease with increasing temperature, but began to rise again at around 400 °C. This behavior is considered to result from the fact that the DIF is a dimensionless value defined as the ratio of the dynamic compressive strength to the static compressive strength; since the static strength decreases more significantly than the dynamic strength, the DIF increases at higher temperatures. In the dynamic property tests of thermally degraded concrete, the specimens were machined after being exposed to elevated temperatures.

However, for specimens that experienced severe degradation, machining was not smooth. Therefore, it is necessary to prepare the specimens first and then expose them to high temperatures before conducting the dynamic property tests.

Based on these findings, regression equations were developed to estimate the dynamic increase factor and the strain at maximum stress for high temperature deteriorated concrete.

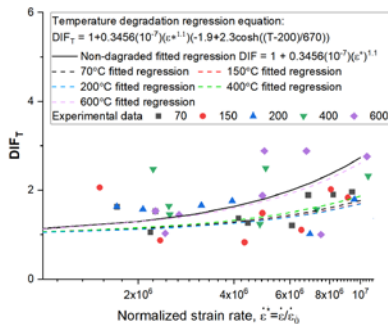


Fig. 3. Regression equation for DIF of thermal degraded

concrete

3. Validation Plan

The strain rate range of 1–10²/s will be validated through free-fall tests of a metal impactor on concrete at a height of 9 meters (equivalent to a velocity of 13.3 m/s). The range of 10²–10³/s will be verified using impact tests on concrete specimens with a Taylor bar impact tester. Additionally, the failure mode, depth, and other factors will be analyzed to conduct a shielding impact assessment.

Table 2. Test equipment and verification methods according to strain rate

Strain rate	Test equipment	Validation methods
1~10 ² /s	Intermediate high speed material test equipment	Drop test
10 ² ~10 ³ /s	Hopkinson bar impact test	Taylor bar impact test

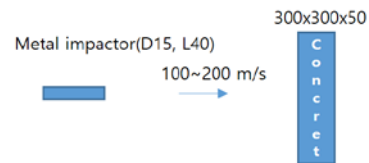


Fig. 4. Schematic diagram of Taylor bar test

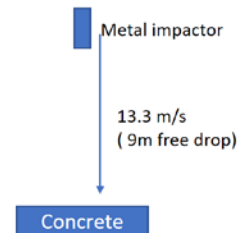


Fig. 5. Schematic diagram of free drop test

Finite element analysis using Abaqus software will be conducted for each test case, and the results will be compared and validated using test results.

4. Conclusions

Dynamic property tests were conducted on concrete specimens exposed to freeze–thaw cycles and high-temperature environments, and dynamic material models were developed. Based on the results, regression equations were established for each degradation mode. The developed dynamic material model will be validated using the data of additional drop and impact tests.