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Durability Performance Evaluation of High-Volume SCM Concrete for Application in Nuclear Power Plants

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ABSTRACT: This study evaluated the durability of concrete substituted with 20% fly ash(FA20) and concrete substituted with 50% ground granulated blast furnace slag(BS50) for use in nuclear power plants. The experimental variables were admixture type and water–binder ratio(*W/B*). The measured durability characteristics were compressive strength and resistance to freezing and thawing. BS50 had lower initial strength but better compressive strength as a function of aging than FA20. The results of resistance against freezing and thawing showed that as the *W/B* decreased the resistance was improved, regardless of admixture type. In particular, resistance against the mass loss rate due to freezing and thawing in the BS50 mix were approximately 1.3 times and 2.2 times higher, respectively, as compared to the FA20. Conclusively, the BS50 was better than the FA20 in terms of freezing–thawing durability.

KEYWORDS: NPP concrete, Durability, Freezing and thawing, Carbonation, Gamma ray.

I. INTRODUCTION

Since domestic nuclear power plants are located in coastal areas for the supply and drainage of cooling water, damage owing to various deterioration factors such as salt damage and sulfate occurs as the number of operating years increases. Furthermore, the containment building of a nuclear power plant structure is composed of a reinforced concrete structure with a thickness of 1.2 m, and it is necessary to control temperature cracks by the difference between the inside and outside temperature [1].

Concrete with 20% fly ash replacement is used for current nuclear power plants to ensure durability and the reduction of hydration heat. Construction is performed in accordance with the Construction Package Specification (CP-C2) and is managed in accordance with the Korea Electric Power Industry Code (KEPIC). However, the reduction effect on the hydration heat of concrete when using 20% fly ash replacement is limited. The ACI 318-99 code limits the replacement rate of fly ash to a maximum of 25% for concrete that simultaneously receives freezing and thawing and chemical weathering such as seawater [2]. On the other hand, the blast furnace slag concrete has a maximum replacement rate of 50%, which is advantageous in ensuring constant quality and reducing hydration heat [3]. To improve the durability and economic efficiency of concrete in nuclear power plants (NPP concrete) and reduce hydration heat, high-performance concrete with high-volume blast furnace slag has been developed and tested [4].

This study investigated the applicability of high-volume blast furnace slag concrete as NPP concrete. A durability characterization and gamma-ray irradiation test of conventional NPP concrete and high-volume blast furnace slag NPP concrete were performed. The experiments were conducted with concrete materials except for the blast furnace slag, which is actually used in nuclear power plants. Conventional NPP concrete is a mix with a 20% replacement of fly ash (FA20), and the new concrete is a mix with a 50% replacement of blast furnace slag (BS50). The test parameters

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include compressive strength according to age, salt damage resistance, freezing and thawing resistance, and carbonation resistance. Radiation durability was characterized by an increase in specimen temperature according to gamma-ray irradiation, as well as changes in the compressive strength and chemical composition before and after the gamma-ray irradiation.

II. MATERIAL AND EXPERIMENTAL METHOD

A. Mix design

The durability characteristics of the NPP concrete were evaluated according to the concrete design strength with respect to the FA20 mix and BS50 mix, and the mix design is shown in Table 1. The concrete design strength with a water-binder ratio of 50% is 4,000 psi (28 MPa), and the design strength with a water-binder ratio of 40% is 5,000 psi (35 MPa) and 6,000 psi (41 MPa). To improve the compressive strength of the 6,000 psi mix, this mix was designed to have a higher binder content than 5,000-psi mix.

Table 1. Mixture proportions

Specimen	*W/B* (%)	Unit weight (kg/m^3)						Design strength
		Water	Cement	FA	BS	Sand	Gravel	
FA20-28	50	163	263	66	-	850	959	28 MPa(4,000 psi)
FA20-35	40	160	323	81	-	728	1023	35 MPa(5,000 psi)
FA20-41	40	163	329	82	-	775	962	41 MPa(6,000 psi)
BS50-28	50	163	163	-	163	856	965	28 MPa(4,000 psi)
BS50-35	40	160	202	-	202	733	1029	35 MPa(5,000 psi)
BS50-41	40	163	206	-	206	779	968	41 MPa(6,000 psi)

B. Materials

The cement has a density and fineness of 3.15 g/cm^3 and 3256 cm^2/g, respectively. Table 2 lists the physical and chemical properties of cement, fly ash, and blast furnace slag. Uljin river sand with a density of 2.77 g/cm^3 was used as the fine aggregate, and Uljin crushed gravel with a maximum dimension of 25 mm and a density of 2.68 g/cm^3 were used as the coarse aggregate (Table 3).

Table 2. Chemical compositions and physical properties of binders

Property		Cement	FA	BS
Density (g/cm^3)		3.15	2.35	2.93
Specific surface area (m^2/g)		3,256	3,426	4,645
Chemical characteristic (%)	SiO_2	20.6	58.4	35.9
	Al_2O_3	5.4	18.4	16.7
	Fe_2O_3	3.5	7.9	0.5
	CaO	60.4	5.3	39.5
	MgO	4.1	1.7	3.8
	SO_3	2.5	-	4.0
	K2O	1.07	1.4	0.51
	Na_2O	0.08	1.5	0.24
	LOI	2.37	2.41	-0.86

Table 3. Physical properties of aggregates

Property	Sand	Gravel
Density (g/cm^3)	2.77	2.68
Absorption ratio (%)	1.33	2.8
0.08-mm passing content (%)	0.91	4.8
Bulk density (kg/m3)	1.702	1.662

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C. Durability test method

The compressive strength of the concrete was measured by using the KS F 2405 concrete strength test method, and a test specimen of ϕ100 mm × 200 mm was prepared and tested for the ages of 3, 7, 28, 56, and 91. For the freezing and thawing resistance, specimens were prepared in accordance with ASTM C 666, and an accelerated freezing and thawing test was performed [5]. The relative dynamic modulus for two specimens of each mix was measured. For the carbonation resistance, test specimens of ϕ100 mm × 200 mm were prepared in accordance with KS F 2584, and an accelerated carbonation test was performed after standard curing for up to 28 days [6]. The carbonation depth was measured at 1, 4, 8, 13, and 26 weeks after the start of the test.

D. Gamma-ray irradiation test

High-level gamma rays and neutrons generate heat inside the containment wall concrete of nuclear power plants. This can lead to a loss of mechanical properties such as compressive strength and relative dynamic modulus, as well as cracks. Thus, thresholds for neutron and gamma-ray irradiation are used in evaluating the strength reduction of NPP concrete. IAEA radiation exposure thresholds are 1×10^{19} n/㎠ for thermal neutrons and 10^8 Gy for gamma rays. ASME limits the exposure to 1×10^{20} n/㎠ for thermal neutrons and 2×10^8 Gy for gamma rays [7-8]. In the APR 1400, which is a Korean-type nuclear power plant, the reactor cavity is the location with the highest total cumulative radiation dose of gamma rays in the FSAR considered in the design of the containment building. The total cumulative radiation dose is 4.9×10^7 Gy in normal operation and 6×10^7 Gy in accidents. These are smaller than the ASME design standard of 2×10^8 Gy for the containment building.

Gamma rays have no significant effect on solid materials composed of ions and metal bonds in NPP concrete. However, the radiation decomposition of pore water and the radiation dehydration of the reaction products can result in micro cracks resulting from covalent bond breakdown and the radiation decomposition process. Heat transfer of the radiation absorbed in concrete affects the physical and mechanical performance degradation of concrete [9-10].

This study conducted a gamma-ray irradiation test to analyze changes in the compressive strength and chemical composition of conventional NPP concrete and high-volume blast furnace slag concrete. The gamma-ray irradiation test was performed at the Korea Atomic Energy Research Institute (KAERI). A specimen of ϕ100 mm × 200 mm was prepared and irradiated with high-level gamma rays for 91 days to evaluate the temperature increase of the specimen and the changes in its compressive strength. The nuclide used was Co-60, and the dose was 4.52×10^6 Gy, which is the maximum testable value. The irradiation was performed for two weeks.

III. EXPERIMENTAL RESULT

A. Fluidity

The target slump and air content were set as 4 ± 1 in (76 mm to 127 mm) and 3.5% to 6.5%, respectively, as provided by the CP-C2. The slump and air content of all mixes satisfied the target performance, and the fluidity values for FA20 and BS50 were similar(Table 4). The used amount of water-reducing admixture increased with an increase in the amount of unit powder compared with the design strength and unit water amount. The used amount of AE admixture for FA20 was approximately two times higher than that of the mix with blast furnace slag. It is typically known that the amount of AE admixture is influenced by the amount of carbon in the fly ash, the loss ignition, the degree of the powder, and the amount of organic material. Among these factors, an increase in the amount of AE admixture according to the use of fly ash is mainly attributed to the AE admixture adsorption of unburned carbon contained in fly ash [11].

Table 4. Result of fluidity

Specimen	Slump (mm)	Air content (%)	AD (%)	AE (%)
FA20-28	95	4.5	0.5	0.010
FA20-35	90	4.0	0.5	0.010
FA20-41	90	4.0	0.6	0.010

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BS50-28	90	4.8	0.5	0.005
BS50-35	100	4.0	0.5	0.005
BS50-41	95	4.0	0.6	0.005

B. Compressive strength

All mixes satisfied the design compressive strength. The compressive strength of BS50 was approximately 20% lower than that of F20 for up to 7 days of age(Fig. 1). However, the long-term compressive strength of BS50 was 1.2 to 1.4 times higher than that of FA20 after 7 days of age. BS50 had an average 20% lower development rate than FA20 at the initial age, while the compressive strength development rate increased rapidly from 28 days of age. The results suggest that blast furnace slag powder reacted with the alkali generated during the hydration process of cement to form a densely structured hydrate matrix, thereby improving the long-term durability [12-13].

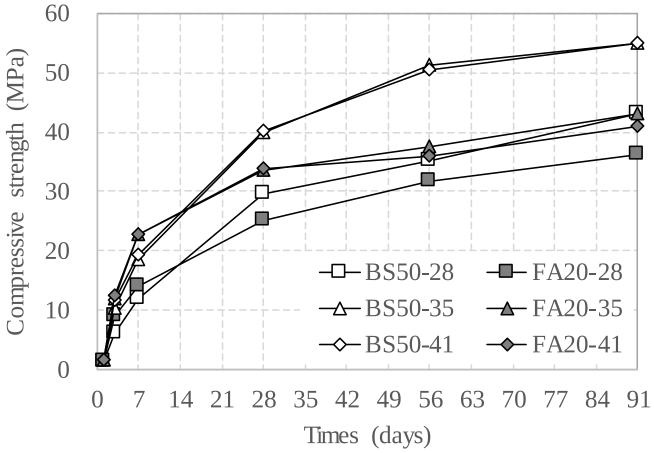

Fig. 1 Test results for compressive strength

C. Carbonation resistance

Figure 2 shows the measurement results of the carbonation penetration depth for NPP concrete. The carbonation depth tended to decrease significantly as the compressive strength increased. In particular, as the target compressive strength increased from 28 MPa to 35 MPa, the carbonation depth was reduced by approximately 70%. Typically, as the compressive strength increases, *W/B* decreases and the porosity rate of the concrete decreases. This decrease in porosity rate improves the carbonation resistance by enhancing the inflow resistance of CO_2 gas [14].
The carbonation resistance of BS50 in the 28 MPa class was improved by approximately 37% compared to that of FA20. On the other hand, the difference in the carbonation depth above 35 MPa between FA20 and BS50 was less than 1 mm, which was insignificant. BS50 was evaluated to have equal or greater carbonation resistance compared to that of conventional NPP concrete.

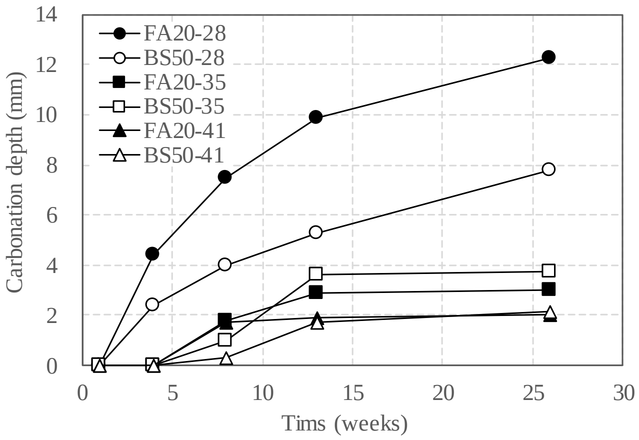

Fig. 2 Test results for carbonation depth

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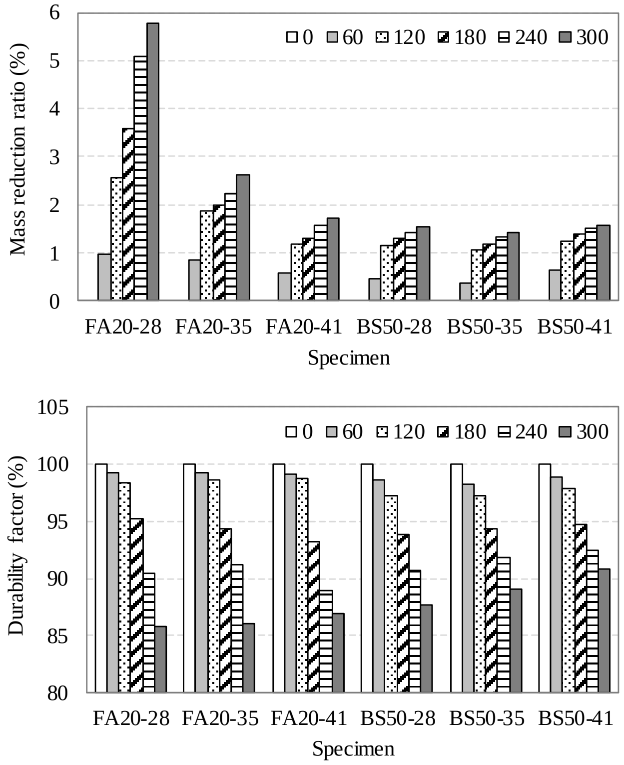
D. Freezing and thawing resistance

Figure 3 shows the mass reduction ratio and the relative dynamic modulus of each cycle according to the accelerated freezing and thawing test. The mass reduction ratio is the mass reduction owing to the detachment of the surface of the concrete owing to freezing and thawing. The lower the mass reduction, the better the freezing and thawing resistance [15-16]. The criterion of the relative dynamic modulus for determining the freezing and thawing resistance is suggested to be 60 or higher at 300 cycles.

The test specimen with the highest mass reduction ratio was FA20-28. The rate of increase of the mass reduction ratio after 270 cycles was reduced, and the rate of decrease at 300 cycles was 5.8%. On the other hand, the mass reduction ratio of BS50 at 300 cycles was 1.5% on average, which was significantly lower than that of FA20. Furthermore, the BS50 specimen showed almost no visible surface detachment at 300 cycles. However, the FA20 specimen showed visible peeling from 180 cycles onward.

The relative dynamic modulus increased as the compressive strength increased. The mean freezing and thawing durability indexes of FA20 and BS50 were 86.3% and 89.2%, respectively. As a result, the durability index of all specimens was 85% or higher, which meant that the freezing and thawing resistance was excellent. The blast furnace slag mix had a superior mass reduction ratio.



(a) Mass reduction ratio of freezing and thawing **(b) Durability factor**

Fig. 3 Result of freezing–thawing resistance

E. Change analysis of the compressive strength and chemical composition for concrete by gamma-ray irradiation

Gamma rays affect the chemical composition and porosity of concrete components to generate heat during the decomposition of chemical components. Heat generation by gamma-ray irradiation of concrete affects the reduction in mechanical performance (such as strength) of concrete. Thus, the effects of gamma-ray irradiation on the compressive strength of concrete owing to temperature history and temperature increases of the specimen were analyzed. Table 5 lists the temperature of the laboratory and the temperature of the specimen according to the gamma-ray irradiation, and

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Figure 4 shows the compressive strength of conventional NPP concrete and high-volume blast furnace slag concrete before and after gamma-ray irradiation.

Table. 5. Temperature record

days	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Average
Lap	16.5	15.1	16	15.4	15.5	15.2	14.6	14	13.1	13.2	13.2	13.2	13.1	12.4	14.32
Specimen	-	37.5	36	38.2	37.4	36.3	34	33	33	31	32.6	31.5	27.7	24.9	33.32

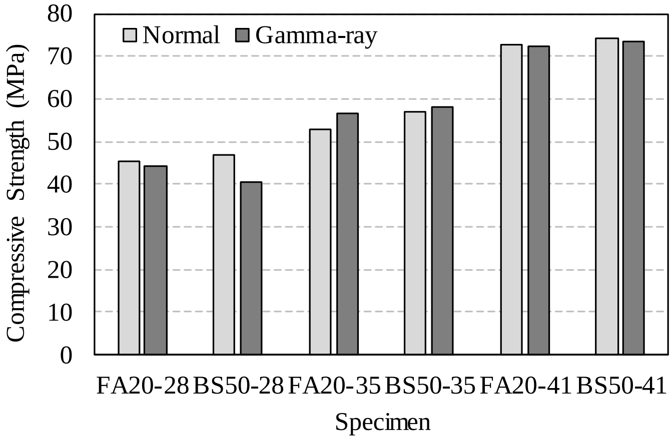

Fig. 4 Effects of gamma-ray radiation on concrete strength

The temperature of the specimen ranged between 24.9°C to 38.2°C, which was 12.5°C to 22.4°C higher than the laboratory temperature. Therefore, the temperature increase of the specimen by gamma rays at a dose of 4.52×10^6 Gy was not significant enough to affect the mechanical performance of the concrete. The number of changes in the compressive strength before and after gamma-ray irradiation was insignificant in all specimens, and the compressive strength for all specimens was observed as being above the design strength. Furthermore, the changes in the compressive strength before and after gamma-ray irradiation of FA20 and BS50 showed similar tendencies. In particular, as the compressive strength increases, the influence of the compressive strength owing to the gamma-ray irradiation is significantly reduced.

The results of the chemical characterization of concrete according to gamma-ray irradiation are shown in Fig. 5. The changes in chemical composition before and after the gamma-ray irradiation were similar to those of FA20 and BS50. Based on a chemical composition analysis, SiO_2 and CaO were the most abundant, accounting for approximately 70% of the total components. SiO_2 was the most abundant. After gamma-ray irradiation, the increase/decrease in the SiO_2 composition ratio and increase/decrease in compressive strength showed similar tendencies.

Generally, the SiO_2 and CaO components are the main compounds forming the C-S-H phase, and the component changes affect the concrete properties. However, to quantitatively evaluate the effects of gamma rays, various evaluations and analyses are necessary, including hydration structure destruction and pore structure analysis through microstructure analysis, as well as the evaluation of internal hydration structure decomposition through TG-DTA.

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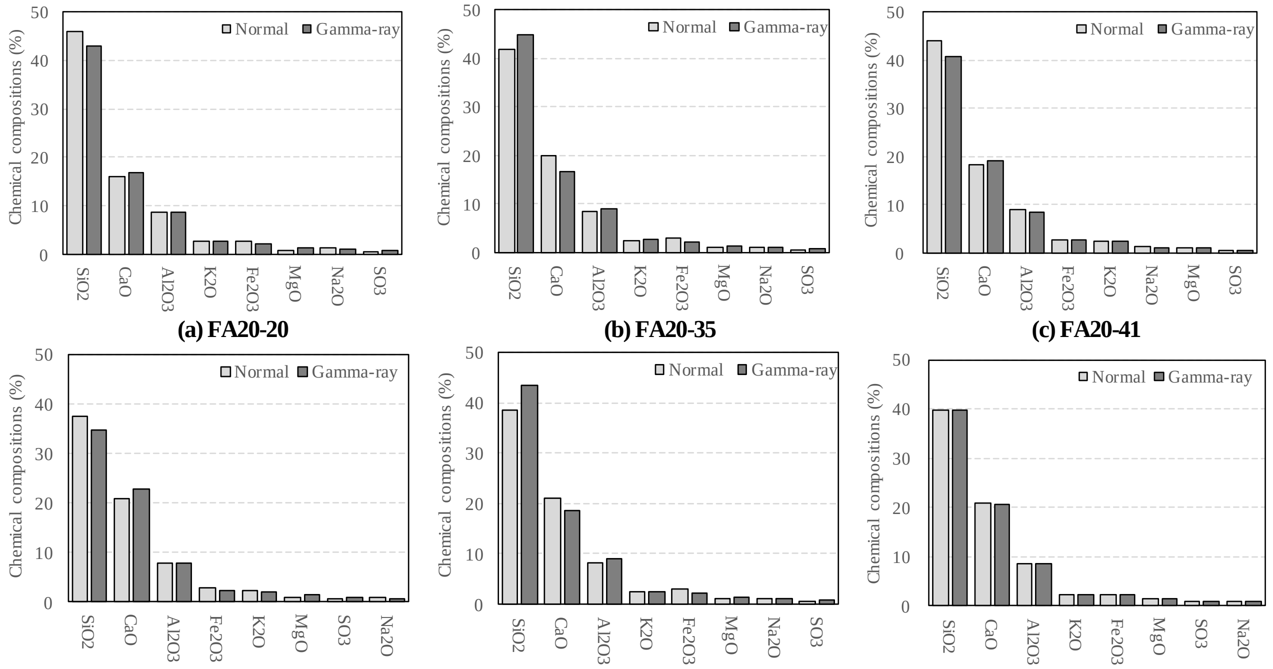

(a) FA20-20 (b) FA20-35 (c) FA20-41
(d) BS50-20 (e) BS50-35 (f) BS50-41

Fig. 5 Chemical compositions

IV. CONCLUSION

In this study, to evaluate the applicability of NPP concrete with a 50% replacement of blast furnace slag, the durability characteristics as well as the compressive strength and chemical composition according to gamma-ray irradiation were investigated in comparison with those of conventional NPP concrete. The durability characteristics of the concrete include its compressive strength and carbonation resistances, and freezing and thawing resistance. The following results were obtained through an investigation of changes in the compressive strength and chemical composition according to gamma-ray irradiation:

1. The compressive strength of concrete with a 50% replacement of blast furnace slag was lower than that of concrete w ith a 20% replacement of fly ash at the initial age. On the other hand, after 28 days of age, the long-term strength of t he concrete with 50% replacement of blast furnace slag was 1.2 to 1.4 times higher than that of concrete with 20% re placement of fly ash.

2. The carbonation depth of concrete with a 20% replacement of fly ash with a design strength of 28 MPa was measure d as approximately 1.6 times higher than that of concrete with a 50% replacement of blast furnace slag. On the other hand, the difference in the carbonation depth from the concrete with a design strength of 35 MPa or higher was insig nificant.

3. The relative dynamic modulus for freezing and thawing was higher with the concrete with a 50% replacement of blas t furnace slag, and all specimens showed excellent freezing and thawing resistance at 85% or higher.

4. The compressive strength of concrete with 50% replacement of blast furnace slag was similar to that of conventional NPP concrete. The increase/decrease in the SiO_2 composition ratio and the increase/decrease in the compressive stren gth after gamma-ray irradiation showed similar tendencies.

5. The durability characteristics, compressive strength, and chemical composition according to gamma-ray irradiation o f concrete with 50% replacement of blast furnace slag were similar to those of conventional NPP concrete. However, for its application to NPP concrete, quantitative evaluations and further investigations are required for constructabilit

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y, long-term durability, influence of neutrons and gamma rays, and shielding performance.

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