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Evaluation of Resistance to Freezing and Thawing and Chloride Attack of High-Performance Concrete Applicable to 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. The measured durability characteristics were compressive strength, chloride-attack resistance 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 chloride attack and freezing and thawing showed that as the water-binder ratio decreased the resistance was improved, regardless of admixture type. In particular, resistance against chloride attack and the mass loss rate due to freezing and thawing in the BS50 mix were approximately 1.3 and 2.2 times higher, respectively as compared to the FA20 mix. Conclusively, the BS50 mix was better than the FA20 mix in terms of chloride attack and freezing-thawing durability.

Key words: Fly ash, ground granulated blast furnace slag, chloride diffusion coefficient, freezing-thawing durability, admixture, resistance

INTRODUCTION

Around 430 nuclear power plants are now operating around the world due to the high resource efficiency of nuclear power as compared to thermal power plants and there are plans to construct another 150 nuclear plants. However, because nuclear power plants produce energy using nuclear fusion, accidents can occur due to radiation and nuclear wastes. To prevent nuclear accidents, concrete is used as one of the main composition materials and radiation shielding materials. Thus, the durability of concrete must be ensured and its verification is critical.

Nuclear power plant containment buildings are designed and constructed to have 1.2 m thick reinforced concrete structures in general. As the thickness of concrete members increases, the heat of hydration can increase inside a concrete member due to the hydration heat of cements and binders. However, the thermal conductivity of concrete is low and thus hydration heat inside the concrete member is only slowly transferred to the outside. Accordingly, the internal and external temperatures of concrete members differ, increasing the probability of cracks in the concrete.

Existing nuclear power plant structures have used concrete substituted with 20% Fly Ash (FA20) to ensure durability and reduce the heat of hydration. Concrete substituted with fly ash has better slump and lower heat of hydration as compared to Ordinary Portland Cement (OPC) in general. However, fly ash is a by-product of coal-fired plants and its quality varies depending on its constituents and amount of energy resource such as oil and coal which is considered as a drawback. Blast furnace Slag (BS) can overcome this drawback. If a large amount of BS is substituted in concrete, the concrete will exhibit lower heat of hydration and higher durability than fly ash-mixed cements (Kim *et al*., 2014).

However, nuclear power plant concrete mixes in current use are designed with a considerably lower substitution rate than the maximum substitution rate of admixtures. Accordingly, it is now necessary to develop and verify high-performance concrete substituted with a large amount of admixtures in order to ensure reduced hydration heat, increased durability and economic feasibility for concrete used in nuclear power plants.

In this study, the durability of existing FA20 concrete and 50% BS-substituted concrete (BS50) was evaluated. The target compressive strengths of the used concretes were 4000-6000 psi and the characteristics to be evaluated for durability were the concrete compressive strength, chloride-attack resistance and freezing-thawing resistance.

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Table 1: Concrete mixes

		Unit weight (kg/m^3)					
Specimen	W/B (%)	Water	C	FA	BS	Coarse agg.	Fine agg.
FA20-4000	50	163	329	66	-	959	850
FA20-5000	40	160	404	81	-	1023	728
FA20-6000	40	163	411	82	-	962	775
BS50-4000	50	163	326	-	163	965	856
BS50-5000	40	160	404	-	202	1029	733
BS50-6000	40	163	412	-	206	968	779

Notation example: FA20-4000 (Fly Ash 20% in a binder and specified design strength of 4000 psi)

Table 2: Analysis of physical and chemical compositions of the binder

Items	OPC	FA	BS
Density (g/cm^3)	3.15	2.35	2.94
Chemical characteristic (%)			
SiO_2	21.55	64.02	36.04
Al_2O_3	5.31	19.89	15.79
Fe_2O_3	3.56	4.45	0.45
CaO	61.23	3.82	42.16
MgO	3.74	1.09	3.94
SO_3	1.95	-0.70	1.95
K_2O	1.08	1.13	0.50
Na_2O	0.13	1.04	0.22
LOI	1.24	6.76	-

Table 3: Analysis of physical compositions of the aggregates

Items	Coarse agg.	Fine agg.
Origin and manufacturer	Shin Uljin	Shin Uljin
Density (g/cm^3)	2.770	2.680
Absorption ratio (%)	1.330	2.800
0.08 mm passing content (%)	0.910	4.800
Unit volume weight (kg/m^3)	1.702	1.662

Experimental design prepare your paper before styling: The experimental design and concrete mixes used to evaluate the durability of concrete for nuclear power plants are shown in Table 1. The Water-Binder (W/B) ratio of the concrete specimens with a 4000 psi design compressive strength was 50% and those with 5000 and 6000 psi design compressive strengths were 40%. However, the binder amount of the 6000 psi mixes was designed to be more than that of the 5000 psi mixes in order to improve the compressive strength of the concrete. The target slump and air amount were set to 100±10 mm and 5.0±1.5%, respectively.

The OPC and FA used in this study satisfied the specification in the ASTM and their physical and chemical properties are shown in Table 2. The coarse aggregates used were crushed aggregates whose maximum size was 25 mm and the fine aggregates used were river sand. The physical characteristics of the aggregates are shown in Table 3.

MATERIALS AND METHODS

Chloride diffusion coefficient: The evaluation of the resistance of the concrete samples to chlorine ion penetration was conducted in accordance with the NT Build 492 acceleration test method. Concrete specimens were cut into 50 mm thick samples. A 0.3 M NaOH aqueous solution at the Anode (+) and a 10% NaCl aqueous solution at the Cathode (-) were filled and an electric potential was applied. The applied voltage was set to 30 V and the initial current (I30 V) was measured to determine the range. The applied voltage was then adjusted to determine the appropriate time according to current (Fig. 1).

Fig. 1: Chloride diffusion coefficient measurement test

Fig. 2: Measurement test of freezing-thawing resistance

Freezing-thawing resistance: The freezing-thawing test was done by manufacturing prismatic specimens (100×100×400 m) and inserting them into the test device to freeze and thaw them for 90, 180, 270 and 300 cycles (ASTM 666). The freezing-thawing resistance was analyzed by measuring the mass loss rate and the relative dynamic modules of elasticity (Fig. 2).

RESULTS AND DISCUSSION

Slump and air amount: The slump and air amounts in the concrete were measured in accordance with ASTM C 213 and ASTM C 143. While mixing the concrete samples a 0.5% admixture was added to the 4000 and 5000 psi mixes and a 0.6% admixture was added to the 6000 psi mix. Table 4 shows the measured air amount and slump according to binder type and W/B. In all mixes, the target air amount of 5.0±1.5% and target slump of 100±10 mm were satisfied.

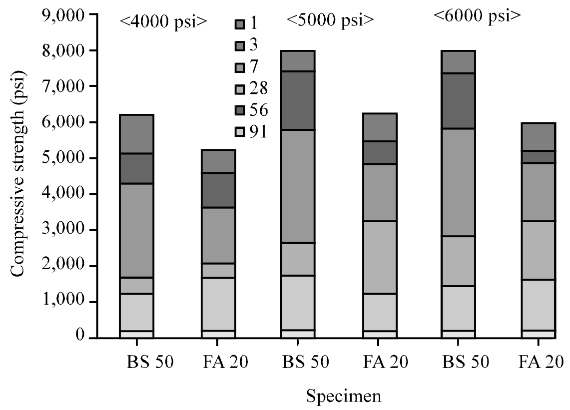

Fig. 3: Test results of compressive strength

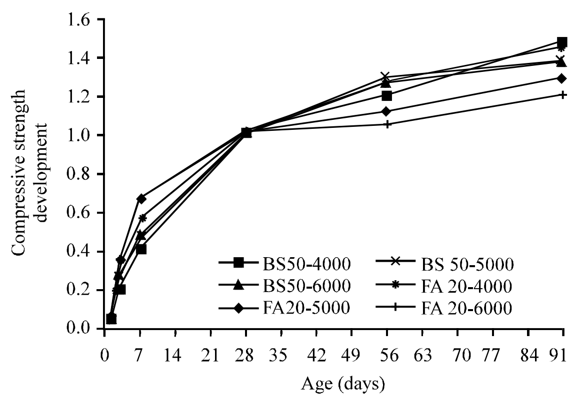

Fig. 4: Compressive strength development

Table 4: Experiment results

Specimen	Slump (mm)	Air (%)	Compressive strength (psi) 7 days	28 days	56 days	91 days
FA20-4000	95	4.5	2040	3644	4606	5249
FA20-5000	90	4.0	3287	4867	5452	6259
FA20-6000	90	4.0	3292	4906	5220	5935
BS50-4000	90	4.8	1711	4273	5104	6259
BS50-5000	100	4.0	2673	5786	7434	7990
BS50-6000	95	4.0	2803	5824	7332	7990

Compressive strength: The compressive strength of the concrete was tested by manufacturing ϕ 100×200 specimens in accordance with the ASTM C 39 test method. The measured compressive strength and its development are shown in Fig. 3 and 4, respectively. All mixes satisfied the design compressive strength regardless of test variables. The compressive strength of the BS50 mix at the initial age of 7 days was approximately 20% lower than that of the FA20 mix. However, at an age of 28 days or longer, the long-term compressive strength of the BS50 mix was 1.2-1.4 times higher than that of the FA20 mix. This result was obtained because microhydrates were formed as the BS fine powder reacted

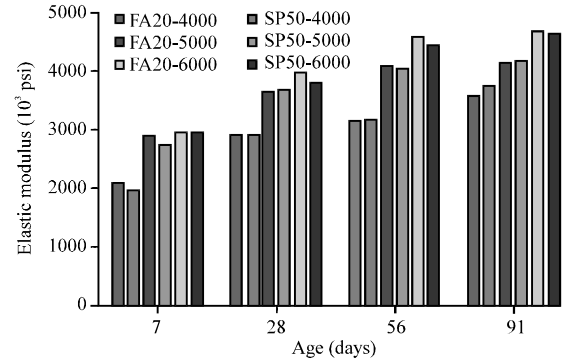

Fig. 5: Modulus of elasticity

with the alkali generated during the hydration process of cement, thereby increasing long-term durability.

The compressive strength development was evaluated based on the compressive strength at an age of 28 days. The FA20 mix showed high strength development at the initial age regardless of the design compressive strength but the rate of increase of the compressive strength was slightly lower after 28 days. On the other hand, the BS50 mix showed 20% lower development on average than the FA20 mix at the initial age but after an age of 28 days, its strength development rapidly increased.

Modulus of elasticity: The modulus of elasticity of concrete is the most important factor in concrete structure design and deflection control. The modulus of elasticity of concrete is affected by a number of variables such as the elastic characteristics and volume ratio of each material, the bonding strength between the coarse aggregate and cement paste, the amount of admixtures, etc. The measured modulus of elasticity showed a large difference by more then 30%, even under the same compressive strength. In this study, the modulus of elasticity was measured and analyzed according to experiment variables such as design strength and admixture substitution rate (Fig. 5).

The modulus of elasticity increased by 14-38% as the target design strength increased from 4000-5000 psi. On the other hand, the modulus of elasticity increased by 4-10% a relatively low rate of increase as the design strength increased from 5000-6000 psi. The initial modulus of elasticity according to admixture type showed that the FA20 mix was 5% higher than that of the BS50 mix on average. However, the difference in the modulus of elasticity according to mix type with a long-term age was minimal. This was due to the delay of the initial strength development caused by the hydraulic potential of the blast furnace slag fine powder and the general trend of long-term strength improvement (CI, 2006).

Table 5: Evaluation of salt damage resistance performance

Compressive strength (psi)	FA20 ($\times10^{-12}$ m^2/sec)	BS50 ($\times10^{-12}$ m^2/sec)
4000	12.30	8.48
5000	7.15	5.61
6000	5.51	5.01

Chloride diffusion coefficient: Because most nuclear power plants are located near coastal regions where the collection and drainage of cooling water are convenient, ensuring the resistance of concrete to chloride attack is critical. In general, concrete forms a dense microstructure inside as it ages. Thus, the chloride diffusion coefficient is significantly reduced as age increases (Elfmarkova *et al*., 2015). Accordingly, this study evaluated the chloride diffusion coefficients of the existing nuclear plant mix (FA20 mix) and the new mix (BS50 mix) based on long-term aging of 91 days (Table 5).

The measured chloride diffusion coefficient at an age of 91 days decreased as the target compressive strength increased. This was because the increasing target compressive strength reduced W/B and increased the amount of binder, thereby making the inner structure of the concrete denser and improving its physical resistance capability. In addition, this was due to the reduction in CsA and CsAF which have been known to restrain the diffusion of chloride in cement (Yang *et al*., 2004).

At 4000 and 5000 psi, the chloride diffusion coefficients of the FA20 mix were approximately 1.5 and 1.3 times higher, respectively than those of the BS50 mix. At 6000 psi, the chloride diffusion coefficient of the FA20 mix was approximately 10% higher than that of the BS50 mix. Conclusively, the measured chloride diffusion coefficient of the new mix (BS50) was 1.1-1.5 times lower than that of the existing mix used in nuclear power plants, thus exhibiting excellent chloride attack resistance. Furthermore, the effect of admixture type and substitution rate on the chloride diffusion coefficient was significantly higher at low strength but it diminished as the strength increased.

Freezing-thawing resistance: In general, the mass loss rate refers to the mass reduction due to peeling off at the concrete surface by freezing and thawing. The lower the mass loss rate, the better the freezing-thawing resistance (Park *et al*., 2011; Ma *et al*., 2013). In addition, the durability index of concrete can be calculated by measuring the relative dynamic modulus of elasticity. Moreover, when the relative dynamic modulus of elasticity of concrete is over 60 after performing 300 cycles of freezing and thawing, it is regarded as having good freezing and thawing resistance.

Table 6: Durability factor of freezing and thawing

Specimen	90 cycle (%)	180 cycle (%)	270 cycle (%)	300 cycle (%)
FA20-4000	99.2	95.2	88.0	85.8
FA20-5000	98.8	94.4	88.8	86.1
FA20-6000	98.9	93.2	87.8	86.9
BS50-4000	97.7	93.8	89.0	87.7
BS50-5000	97.7	94.4	90.6	89.1
BS50-6000	98.3	94.7	91.4	90.8

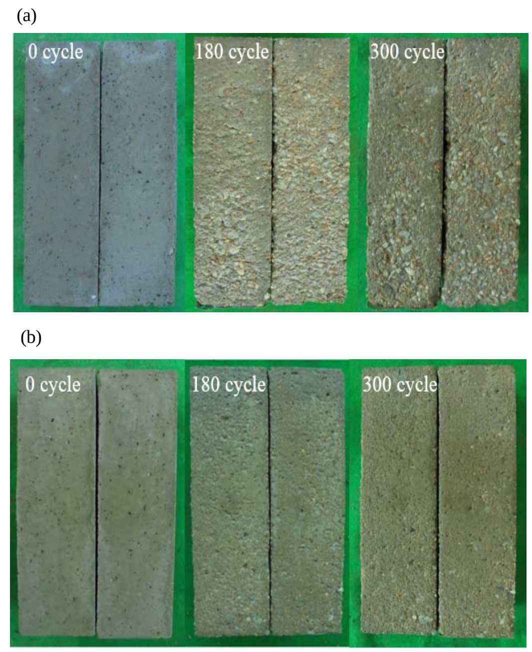

Fig. 6: Freezing and thawing resistance performance: a) FA 20-4000; b) BS 50-4000

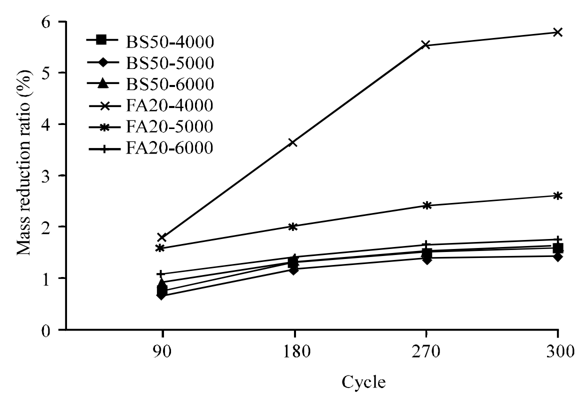

Fig. 7: Mass reduction ratio of freezing and thawing

In order to evaluate the freezing-thawing resistance, the relative dynamic modulus of elasticity and weight reduction rate at each cycle were analyzed (Fig. 6). A mass loss rate and dynamic modulus of elasticity of the specimens according to each cycle of freezing and thawing are exhibited in Fig. 7 and Table 6.

A mix that showed the highest mass reduction ratio was FA20-4000 in which the increased rate of the mass reduction ratio was reduced after 270 cycles and the reduction ratio at 300 cycles was 5.8%. The mass reduction ratio at 300 cycles in the BS50 mix was 1.5% on average which was significantly lower than that of FA20. The durability index of freezing and thawing in all specimens was 85% or more indicating the excellent freezing and thawing resistance of the specimens. The freezing-thawing resistance increased as the compressive strength increased. The mean durability indexes of freezing and thawing in the FA20 and BS50 mixes were 86.3 and 89.2%, respectively.

Conclusively, the difference in the durability index of freezing and thawing between the BS50 and FA20 mixes was relatively small. Nonetheless, the mass loss rate of the FA20 mix was significantly higher than that of the BS50 mix which indicated that the BS50 mix had better freezing-thawing resistance than the FA20 mix.

CONCLUSION

This study measured and analyzed the chloride attack resistance and the freezing-thawing resistance of concrete mixes used in nuclear power plant structures and the following conclusions can be drawn.

The compressive strength of the BS50 mix at the initial age of 7 days was approximately 20% lower than that of the F20 mix whereas the long-term compressive strength of BS50 after an age of 28 days was 1.2-1.4 times higher than that of the FA20 mix. The strength development of the BS50 mix was 20% lower than that of FA20 on average at the initial age but it increased rapidly after an age of 28 days.

The initial modulus of elasticity of the FA20 mix was 5% higher than that of BS50 on average but the difference in the modulus of elasticity at the long-term age according to mix type was minimal.

The chloride diffusion coefficient of the BS50 mix was measured to be 1.1-1.5 times lower than that of the mix currently used in nuclear power plants, demonstrating the excellent chloride attack resistance of the BS50 mix. In particular, the effect of admixture type and substitution rate on chloride diffusion coefficient was significantly higher at low strength but it decreased as the strength increased.

The average mass reduction ratio for the BS50 mix after 300 cycles was 1.5% which was significantly lower than that of FA20. The mean durability indexes of freezing and thawing in the FA20 and BS50 mixes were 86.3 and 89.2%, respectively showing that both materials were excellent.

In conclusion, the initial strength development of the BS50 mix tended to be relatively low whereas the long-term strength and chloride attack and freezing and thawing resistance were better than those of existing mixes used in nuclear power plants.

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