Pergamon

Cement and Concrete Research 32 (2002) 23–30

CEMENT AND CONCRETE RESEARCH

Enhanced durability performance of fly ash concrete for concrete-faced rockfill dam application

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Received 6 November 2000; accepted 18 July 2001

Abstract

The main purpose of this research was to enhance the durability in both the design and construction of dams. Especially, in case of rockfill dams, the durability of face slab concrete in a concrete-faced rockfill dam (CFRD) is achieved by optimizing the fly ash replacement for cement. The effect on durability corresponding to the increasing replacement of fly ash was evaluated, and the optimum value of fly ash replacement was recommended. The results show that 15% of fly ash replacement was found to be an optimum level and demonstrated excellent performance in durability. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Durability; Fly ash; Shrinkage; Permeability; Fatigue

1. Introduction

Considering the important fact that a dam is a "permanent" structure, it is needless to stress the importance of durability of concrete, which is diminished due to varying water levels, freezing and thawing, water penetration, crack, etc.

Table 1 shows the cause of damage in concrete dams in America, Canada and Japan [1]. As given in Table 1, the causes of damage in concrete dams are freezing, water penetration, degradation, and erosion. Therefore, it is important that durability of concrete in dams be enhanced.

Many facts were considered in order to enhance the durability of concrete. Among them is the fact that fly ash concrete enhances both freshly mixed concrete and hardened concrete by pozzolanic reaction [2–5]. It was found that the durability of concrete was improved when some of the cement was replaced by fly ash [2–7].

As the amount of fly ash replacement increased, the durability of concrete improved, but during the initial stages, the compressive strength of fly ash concrete was lower than that of ordinary Portland cement (OPC) concrete, because strength development was slow [2,3,5]. Therefore, fly ash concrete with strength accelerator admixture was being used in some developed countries.

In this study, to enhance the durability of concrete-faced rockfill dam (CFRD), fly ash was mixed with face slab concrete in order to make the material of surface an impermeable wall. An examination of the durability of fly ash concrete was also carried out. As a result, the optimal fly ash concrete, which satisfied the durability and economic efficiency requirements, was developed and applied. The results obtained in this examination would be useful in establishing mixture proportions for fly ash replacement of dam concrete.

2. Experimental program

2.1. Material properties

Type I OPC, produced in Korea and which satisfied ASTM C 150, was used. Physical and chemical properties of cement are shown in Table 2. River sand and gravel, produced in San-chung, Kyung-nam, were used as fine and coarse aggregates, respectively. Physical properties are shown in Table 3.

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PII: S0008-8846(01)00623-8

Table 1
Cause of damage in concrete dams [1]

Classification	America (%)	Canada (%)	Japan (%)	Korea (%)
Overflow	23.7	–	5.3	9.7
Penetration	–	6.7	2.6	3.1
Leakage	28.9	–	10.5	13.1
Erosion	7.9	–	18.4	8.8
Sliding	5.3	13.3	–	6.2
Freezing	–	53.3	23.7	25.7
Earthquake	–	–	–	0
Degradation and deformation	21.1	–	26.3	15.8
Defect of execution	5.3	–	2.6	2.6
Damage of spillway	7.9	26.7	–	11.5
Others	–	–	10.5	3.5
Total	100	100	100	100

Fly ash, produced in Samchonpo and which satisfied ASTM C 618-97, was also used. Physical properties are shown in Table 4. High-range water reducing AE agent was used to obtain the target slump and air content in concrete. A total of four different mixtures were produced. Table 5 shows mixture proportions of concrete with fly ash replacement.

2.2. Test methods and procedure

The main objective of this research was to assess and improve the long-term durability of face slab concrete in CFRD. For the assessment of long-term durability, accelerated aging tests in laboratory were adopted in order to simulate long-term field exposure conditions. The following accelerated aging conditions were considered: compressive strength test, drying shrinkage test, adiabatic temperature rise test, test for resistance to penetration of chloride ion, abrasion resistance test, repeated wetting and drying test, fatigue resistance test and repeated freezing and thawing test.

2.3. Compressive strength test

Twenty-one specimens, aged 7, 28 and 91 days, for the four types of concrete were made, and tests were carried out according to ASTM C 39-96 (Test Method for Compressive Strength of Cylindrical Specimens).

2.4. Drying shrinkage test

The specimens of 100 × 100 × 285 mm were used. This test was carried out according to ASTM C 157. After removal of forms, the specimens were water-cured in standard curing room, with humidity and temperature controller (at the condition of 23.0 ± 1.7 °C and 50 ± 4%). The strain was measured, and drying shrinkage of specimens was calculated using Eq. (1).

$$\Delta = \frac{(x_{01} - x_{02}) - (x_{i1} - x_{i2})}{L_0} \quad (1)$$

where Δ is the quantity of drying shrinkage; x_{01}, x_{02} are the observed values of basic time; x_{i1}, x_{i2} are the observed values of time 1; and L_0 is the standard length.

2.5. Adiabatic temperature rise

The rise of internal temperature due to heat of hydration of concrete, which varied with fly ash replacement, was estimated, and the effect of adiabatic temperature rise of concrete was analyzed. In this study, concrete calorimeter was used, and the values were measured per 30 min for 14 days just after placement.

2.6. Chloride ion penetration

This test was carried out according to ASTM C 1202-97 (Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration) to measure the quantity of chloride ion penetration [8].

This test measures the quantity of chloride ion, which many penetrate the specimen after 6 h using electrical indicator. The test specimens were water-cured for 28 and 91 days.

2.7. Abrasion resistance

This test was carried out to evaluate the performance of fly ash in concrete with respect to abrasion resistance according to ASTM C 779-95 (Abrasion Resistance Horizontal Concrete Surfaces) [9], Procedure B and Dressing wheels with specimens of 300 × 300 × 150 mm, which were water-cured for 28 and 91 days. The speed of revolution of dressing wheels was 56 rpm. The depth of abrasion was measured after 30 and 60 min of exposure to the abrasive force.

2.8. Repeated wetting and drying

Repeated wetting and drying cycles, simulating repeated rain and heat conditions in natural weather, promote some chemical and physical mechanisms in CFRD. A total of

Table 2
Physical and chemical properties of cement

Classification	Specific gravity	Fineness (cm^2/g)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	Mgo (%)	SO_3 (%)	Ignition loss
Cement	3.15	2900	21.1	6.5	2.9	62.5	3.3	2.2	1.0

Table 3
Physical properties of aggregates

Type	Maximum size	Fineness modulus	Specific gravity	Water absorption (%)	Unit weight (kg/cm^2)	Abrasion (%)	Soundness (%)
Fine aggregates	–	2.84	2.62	1.61	1.74	–	5.0
Coarse aggregates	25	–	2.73	1.40	1.77	22.4	4.4

Table 4
Physical properties of fly ash

Classification	Loss on ignition (%)	Unit quantity of water (%)	Fineness (cm^2/g)	Specific gravity	SiO_2 (%)	Water content (%)
ASTM standard	Less than 6	Less than 105	More than 2,400	More than 1.95	More than 45	Less than 1
Fly ash produced in Samchonpo	3.6	101	3,960	2.25	55	0.2

25 cycles of wetting/drying were used. Because there was no standard test method, in each cycles, specimens were kept moist into the water bath for 12 h at 30 °C, and then dried for 12 h at 60 °C in the oven. After wet and dry repetition tests, physical change was examined through the compressive strength test.

2.9. Fatigue resistance

Fatigue is a process of progressive, permanent, internal, structural change in a material subjected to repetitive stresses. These changes may be damaging and may result in progressive growth of cracks and complete fracture if the stress repetitions are sufficiently large.

This test was used to simulate the resistance of concrete to fatigue, which may have occurred due to varying water pressures. This test was carried out according to the method recommended by ACI. Specimens of 150 × 150 × 600 mm were used in flexural strength tests, and the test was carried out according to ASTM C 78-94 (Test Method for Flexural Strength of Concrete). In the fatigue resistance test, the specimens of 150 × 150 × 1500 mm were made, and 75%, 65%, and 55% of fracture strength obtained through flexural strength tests were decided as repeated loads. Cycles of fracture were measured and $S-\log N$ diagram was analyzed through S_{max} (maximum applied load/ultimate load) and number of cycles (N) of each specimens.

2.10. Water penetration

In general, the permeability of concrete is regarded as a fundamental material property governing the durability of concrete, particularly in structures exposed to environment.

This test was used to examine the characteristic of water penetration of fly ash concrete and to determine the coefficient of permeability of concrete. Because there was no standard test method, this test was carried out according to U.S. Department of the Interior-Bureau of Reclamation method. An external pressure water penetration instrument was used in this test to make one side of the specimen airtight, pressurize water through that side and allow water to penetrate out from the opposite side. The coefficient of permeability was determined by measuring the amount of water passing using the Darcy's law and the equation of continuity.

2.11. Repeated freezing and thawing

This test investigates the possible degradation of cement-based materials exposed to repeated freezing and thawing (F&T) cycles. Freezing of water in the mortar capillary pores, owing to the volume increase of water upon turning to ice, would cause internal pressures that lead to cracking and deterioration of concrete [6].

This test was used to analyze the effect on concrete resistance to specific cycles of freezing and thawing. It was

Table 5
Mixture properties of dam concrete

Fly ash replacement level (%)	σ_{28} (MPa)	Maximum size (mm)	Slump (cm)	Air concrete (%)	W (kg/m^3)	C (kg/m^3)	FA (kg/m^3)	W/B (%)	S/A (%)	S (kg/m^3)	G (kg/m^3)	AD (g/m^3)
0	20.6	25	6 ± 1.5	4 ± 1.5	159	326	0	48.8	43	783	1085	489
10	20.6	25	6 ± 1.5	4 ± 1.5	164	274	27	54.5	44	804	1065	602
15	20.6	25	6 ± 1.5	4 ± 1.5	164	263	39	54.2	44	802	1062	755
20	20.6	25	6 ± 1.5	4 ± 1.5	164	251	50	54.4	44	801	1061	903

Abbreviations: W, water; C, cement; FA, fly ash; W/B, water/binder ratio; S/A, sand/aggregate; S, sand; G, gravel; AD, admixture.

Table 6
Compressive strength test

	Compressive strength (MPa)		
Type	σ_7	σ_{28}	σ_{91}
OPC	16.6	21.0	23.6
F/A = 10%	17.2	22.8	29.9
F/A = 15%	14.1	22.2	25.4
F/A = 20%	11.9	20.7	24.1

carried out according to ASTM C 666-92 (Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing) [10]. Durability factor, dynamic modulus of elasticity and maximum number of cycles were determined through the test to examine the effects on concrete when the concrete structures are subjected to freezing and thawing action and when expansion pressure of concrete exceed the tensile strength.

3. Experimental results

3.1. Compressive strength test

Compressive strengths were measured at the ages of 7, 28 and 91 days, and the results are shown Table 6 and Fig. 1.

At the age of 7 days, the compressive strength of OPC was higher than that of fly ash concrete; however, as the age increased, the compressive strength of fly ash concrete became higher relative to that of OPC. This was primarily because sufficient pozzolanic action of the fly was activated. In Fig. 1, fly ash concrete was more effective than OPC in long-term strength, which was obtained by 10% fly ash replacement.

3.2. Drying shrinkage

The results of the drying shrinkage test in varying fly ash replacements are shown in Table 7 and Fig. 2.

Table 7
Drying shrinkage test (microstrain)

Ages (days)	OPC	F/A = 10%	F/A = 15%	F/A = 20%
1	0	0	0	0
3	5	18	10	15
7	8	20	17	21
14	43	23	34	51
21	47	36	36	60
28	52	47	69	72
35	56	55	74	85
42	60	61	93	93
49	62	70	95	103
56	72	73	108	108
63	74	77	118	118
70	76	83	121	124
77	78	87	123	126
84	85	89	130	128
91	89	93	134	137

In case of this test, drying shrinkage was lower in OPC than in fly ash concrete except for the 10% fly ash replacement in both short and long ages, as shown in Fig. 2. Drying shrinkage of the 10% fly ash replacement was lower than that of other fly ash concrete in both short and long ages.

3.3. Adiabatic temperature rise

The results of the adiabatic temperature rise test in varying fly ash replacements are shown in Table 8 and Figs. 3 and 4.

Fig. 3 shows the change of value of adiabatic temperature rise in varying fly ash replacements. In this test, for the 10% fly ash replacement concrete, the value of adiabatic temperature rise decreased. It increased for the 15% fly ash replacement. In addition, Fig. 4 shows the change in reaction rate. The reaction rate decreased in the varying fly ash replacements. The reaction rate decreased because fly ash restrained or retarded temporarily the reaction of hydration, and as the amount of fly ash replacement was increased, this tendency became more apparent. The values of adiabatic temperature rise and reaction rate obtained

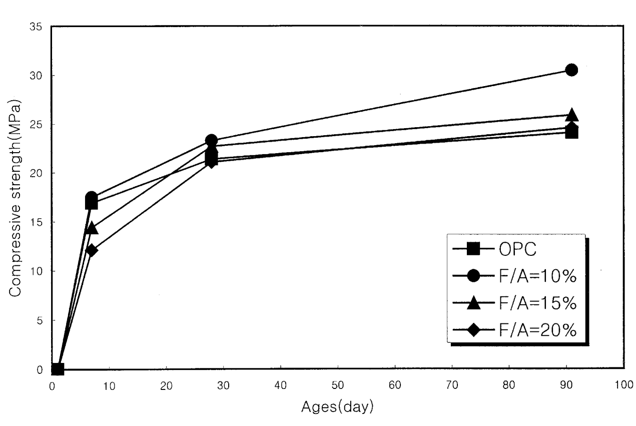

Fig. 1. Compressive strength test in varying fly ash replacements.

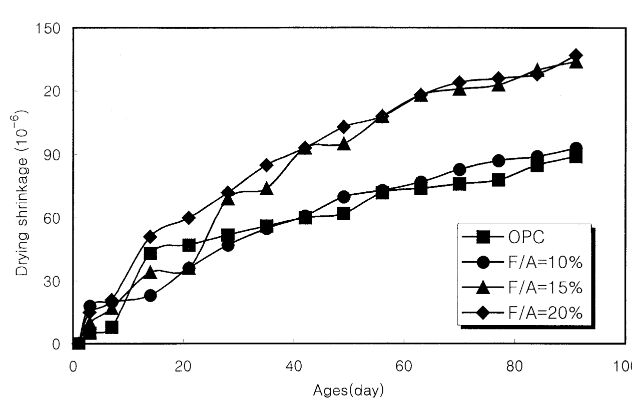

Fig. 2. Drying shrinkage test in varying fly ash replacements.

Table 8
Adiabatic temperature rise test

Type	Value of adiabatic temperature rise (K)	Reaction rate (α)
OPC	46.7	1.7
F/A = 10%	43.3	0.9
F/A = 15%	44.7	0.8
F/A = 20%	46.5	0.6

through this test will be applied to analyze the possibility of crack development due to thermal stress.

3.4. Chloride ion penetration

The amount of electric charge passing through the concrete was used not to obtain the exact coefficient of permeability but to estimate the approximate characteristic of permeability of concrete. After the specimens are water-cured for 28 and 91 days in varying fly ash replacements, results obtained are shown in Fig. 5.

Considering the amount of charge passed, estimated at the ages of 28 and 91 days, when fly ash replacement was 15%, permeability resistance was shown to be most effective. Generally, when fly ash and blast furnace slag is added to concrete, the fabrication of concrete is dense and the efficiency of permeability is low. This test results were in agreement with the general tendency.

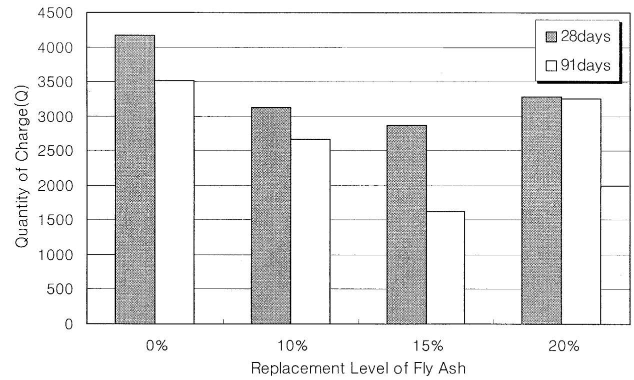

Fig. 5. The amount of passing charge in varying fly ash replacements.

3.5. Abrasion resistance

The results of the abrasion resistance test are shown in Fig. 6. In Fig. 6, the results indicated that the greater the amount of fly ash replacement, the better the abrasion resistance was. In 30 min of abrasion time, the specimens with the 10% fly ash replacement were two times better than those of the OPC, 3.3 times than that of the 15% fly ash replacement and 3.6 times better than the 20% fly ash concrete. In 1 h, the specimens with the 10% fly ash replacement were 1.3 times better than those of the OPC, 2.8 times better than the 15% fly ash replacement and 4.3 times better than the 20%. However, when the 15% fly ash concrete was compared with the 20%, the amount of abrasion was almost the same in 30 min of abrasion time, and there was almost no change after 1 h. However, at the age of 91 days, the results of the abrasion resistance test were best for the 15% fly

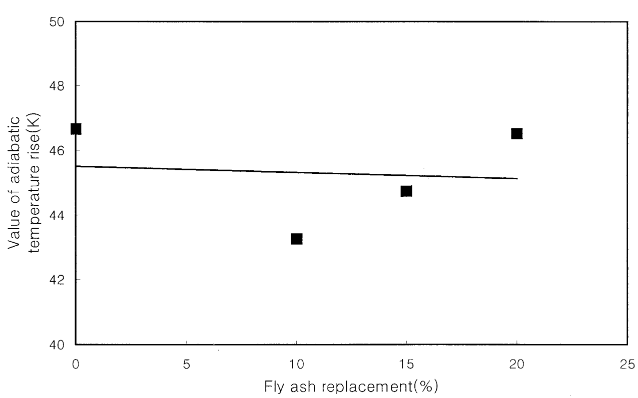

Fig. 3. Adiabatic temperature rise test in varying fly ash replacements.

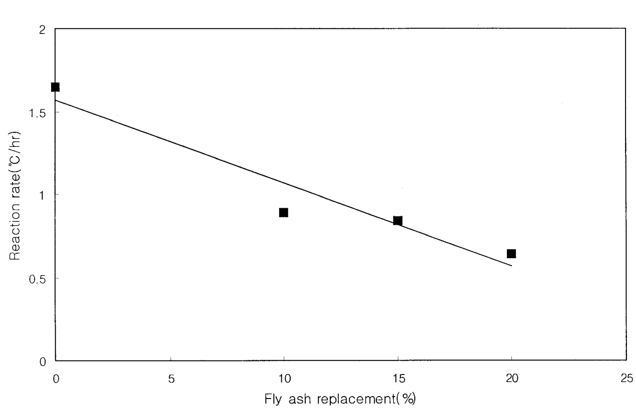

Fig. 4. Reaction rate test in varying fly ash replacements.

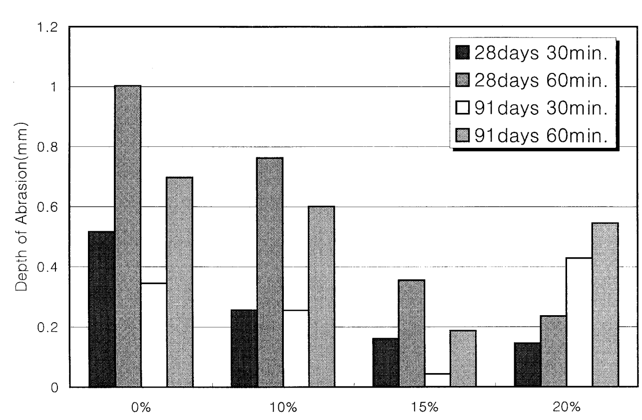

Fig. 6. Abrasion resistance test.

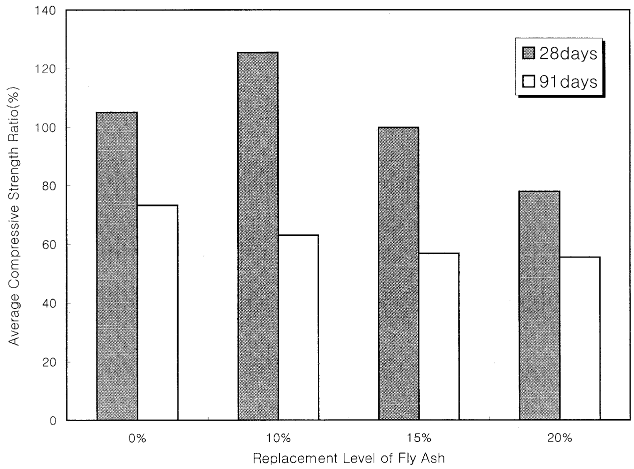

Fig. 7. Repeated wetting and drying test.

ash replacement, and the amount of abrasion increased more than that at the age of 28 days for the 20% fly ash concrete. Generally, when fly ash is added to concrete, water repellence and durability increase, but this test showed that the results were best for the 15% fly ash replacement.

3.6. Repeated wetting and drying

The ratio of average compressive strength is shown in Fig. 7. The ratio of average compressive strength is defined as the ratio of the strength of the specimens having undergone the wet and dry repetition test to the specimens when water-cured. In Fig. 7, the ratio decreased in both the ages of 28 and 91 days when the replacement of fly ash was increased. It is worth noting that compressive strength at the age of 91 days was considerably affected.

3.7. Fatigue resistance

The results of the flexural strength test performed before the fatigue resistance test are shown in Fig. 8. The flexural strength was highest in the 10% fly ash replacement and as the replacement level of fly ash was increased, the flexural strength decreased, as illustrated in Fig. 8.

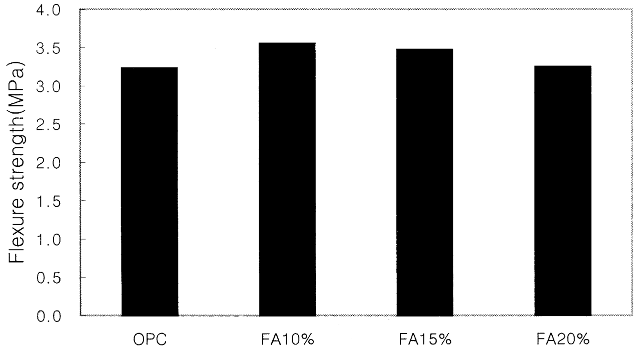

Fig. 8. Flexure strength test.

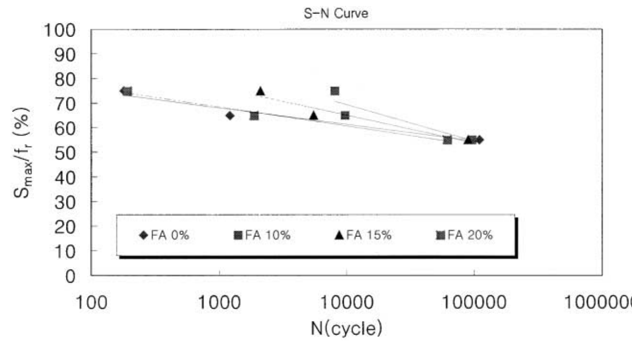

Fig. 9. Fatigue resistance test in varying fly ash replacements.

The S–N curve to the replacement level of fly ash was shown in Fig. 9. When S_{max} was 55%, though decreasing in the order of 0%, 10%, 15% and 20% fly ash concrete, the result was almost the same except for the 20% fly ash concrete.

3.8. Water penetration

Runoff per unit hour and the coefficient of permeability to examine water repellence in proportion to fly ash replacement are shown in Table 9.

As the amount of fly ash replacement was increased, the coefficient of permeability of each age decreased and water repellence increased, as shown in Table 9.

Due to the limited number of specimens, it was difficult to quantitatively compare the efficiency of water repellence; however, it showed demonstrable improvement in efficiency of repellence correlated with the increase in fly ash replacement and ages.

Table 9
Comparison of the efficiency of water repellence in varying fly ash replacements

Specimens	Ages (days)	Runoff in unit hour (Q) (mm^3/s)	Coefficient of permeability (K) ($\times 10^{-11}$ mm/s)	Remarks
15%	56	1.9	12.6	
20%		1.2	8.2	
20%		1.3	8.8	
10%	91	6.0	35.4	Another
10%		6.5	38.2	instrument
20%		5.5	31.9	is used
OPC		1.0	6.7	
15%		0.2	1.8	
15%		0.4	2.6	
OPC	105	0.5	3.2	
OPC		0.4	2.5	
10%		0.3	2.1	

Table 10
Decreased ratio of weight and relative dynamic modulus of elasticity in each cycle

Replacement level	Type of measurement	Cycle 0	35	70	105	140	175	210	245	280	300
0%	Decreased ratio of weight (%)	0	0.67	0.93	1.07	1.23	1.24	1.27	1.28	1.31	1.39
	Relative dynamic modulus of elasticity (%)	100	98.4	97.4	96.1	95.5	94.7	91.2	89.7	87.3	86.6
10%	Decreased ratio of weight (%)	0	1.55	1.86	2.36	2.71	2.78	2.84	2.89	3.01	3.22
	Relative dynamic modulus of elasticity (%)	100	98.1	97.1	95.3	94.4	94.2	93.4	93.2	92.4	90.1
15%	Decreased ratio of weight (%)	0	0.53	0.81	0.92	1.12	1.15	1.23	1.24	1.29	1.41
	Relative dynamic modulus of elasticity (%)	100	99.4	99.9	98.8	97.7	97.6	97.0	96.3	95.2	94.1
20%	Decreased ratio of weight (%)	0	0.57	0.90	1.16	1.46	1.52	1.52	1.55	1.59	1.69
	Relative dynamic modulus of elasticity (%)	100	99.3	98.8	98.3	98.1	97.4	97.5	96.6	96.2	95.3

3.9. *Repeated freezing and thawing*

Until 300 cycles, the average decreased ratio of weight and the average relative dynamic modulus of elasticity are shown in Table 10, and the results are shown Figs. 10 and 11.

Because all tests were terminated in 300 cycles, the relative dynamic modulus of elasticity in 300 cycles was used as the durability factor. In Fig. 10, the specimen with the 10% fly ash replacement showed the relatively highest value of the average decreased ratio of weight. In Fig. 11, the result of the related dynamic modulus of elasticity was shown to be the most effective for the mixtures of 15% and 20% fly ash replacement since it indicated that a durability factor of 85% until 300 cycles is generally regarded as very satisfactory.

4. Conclusions

(1) For the result of chloride penetration test, estimated at the ages of 28 and 91 days, considering the amount of charge past, fly ash replacement of 15% was shown to be most effective for increasing permeability resistance.

(2) For the result of the abrasion resistance test, at the age of 28 days, as replacement of fly ash was increased, the efficiency of abrasion resistance increased. While at the age of 91 days, the efficiency of abrasion resistance increased up to 15% of fly ash replacement, while for 20% fly ash replacement, its effectiveness showed a decrease.

(3) For the result of the wet and dry repetition test, when replacement level of fly ash was 15%, the resisting efficiency was most effective.

(4) For the result of the water penetration test, it showed a tendency that as the amount of fly ash replacement and ages increased, the efficiency of water repellence was enhanced.

(5) For the result of the repeated freezing and thawing test, the relative dynamic modulus of elasticity was shown to be the most effective for the mixtures of 15% and 20% fly ash replacement.

Through the above results, it was concluded that the 15% fly ash replacement would be recommended as the optimum mixture for the overall durability of dam concrete.

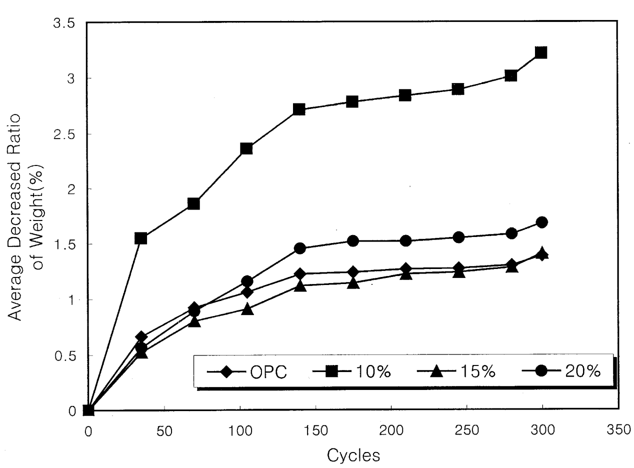

Fig. 10. The average decreased ratio of weight in each type.

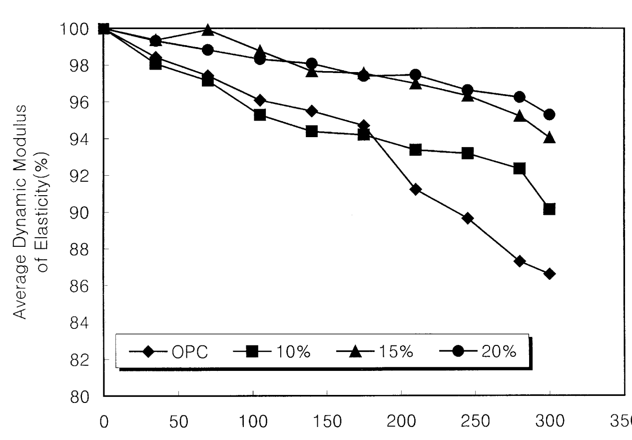

Fig. 11. The relative dynamic modulus of elasticity in each cycles.

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