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Strength deterioration of high strength concrete in sulfate environment

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Abstract

Sulfate in soil and groundwater may cause damage to the concrete in underground structures. In this paper, laboratory tests were performed to assess the damage of chemical attack by magnesium sulfate and sodium sulfate on normal and high strength concretes. The selected solutions were pure water and 10% sulfate solutions (sodium and magnesium), which were determined by consideration of the soil environment in Korea. The parameters in experimental programs were water-binder ratio, silica fume content, and the compressive strength of concrete. Observed differences in the characteristics between normal and high strength concretes are discussed, and a scheme for maximizing the resistance of high strength concrete against various kinds of sulfates is suggested.

Keywords: Compressive strength; Durability; Physical properties; Silica fume; Sulfate attack

1. Introduction

Durability of concrete in underground structures depends on the chemical properties of the soil and groundwater. Sulfate-infested or acid environment caused by industrial wastes or chemical residues in reclaimed ground is one of the severe conditions for durability of the concrete. Unfortunately, underground or underwater concrete structures can sometimes be exposed to sulfates and acids, because water-soluble sulfate exists widely in soil, groundwater, streams, and seawater. It has been recognized for a long time that the sulfate induces damage to concrete. Verbeck [1], Lea [2], and Mehta [3] reported that the use of low water-cement ratio or the use of admixture, such as air entraining admixture, pozzolan, or blast furnace slag, would be the most effective treatment for reducing the sulfate-induced damage. Mehta [3] and Lawrence [4] pointed out that increasing the content of C_3A in the cement composition was very effective in decreasing steel corrosion, but resulted in the lower resistance for sulfate attack. Mehta [5] as well as Cohen and Bentur [6] reported that ettringite was produced by the chemical reaction of sulfate and cement, which leads to expansion, cracking, and strength reduction of concrete. Recently, high strength concrete or high performance concrete has come into use for structural or durability purposes. Silica fume may be one of the major admixtures for high strength concrete. Cohen and Bentur [6] and Bentur et al. [7] studied the effect of silica fume in pastes and concretes immersed in 20 and 25% of magnesium sulfate, magnesium chloride, and sodium sulfate solutions. According to their test results and those of Silva Filho and Agopyan [8], the use of Portland cement with silica fume was highly effective for reducing the deterioration by sodium sulfate solution, but did not seem to be effective for the attack by magnesium sulfate solution.

In this paper, the resistance of high strength concrete to sulfate attack was investigated. Laboratory tests and field studies were performed to study the chemical attack by magnesium sulfate and sodium sulfate on normal and high strength concretes. The selected solutions were pure water and 10% sulfate solutions, which were determined by consideration of the soil environment in Korea. The selected parameters in this study were water-cement ratio, silica fume content, and the compressive strength of concrete. Differences observed between the characteristics of normal and high strength concretes are discussed and a scheme for maximizing the durability of high strength concrete in various kinds of sulfates is suggested.

2. Experimental programs

Two kinds of tests were performed during 270 days. In the first one (test I), the sulfate attack on normal and high strength concretes was evaluated by the change in the com-

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Table 1
Mix proportions for test I and test II

Tests	Specimen	W/B	Cement (kg/cm^3)	Water (kg/cm^3)	Fine aggregate (kg/cm^3)	Coarse aggregate (kg/cm^3)	Superplasticizer (kg/cm^3)	Silica fume (%)	Slump (cm)	Compressive strength at 28 days (MPa)
Test I,	OPNSC	0.54	300	162	980	1,000	0	0	8	22.6
Test II	OPHSC	0.36	450	162	730	1,100	1.0	0	13	49.0
	SFHSC	0.36	400	158.4	730	1,150	1.0	10	11	61.8
	HSC-S0	0.28	483	135.3	756	1,124	1.7	0	10	66.7
	HSC-S5	0.28	463	135.4	756	1,124	1.7	5	8	69.6
	HSC-S10	0.28	430	131.9	756	1,124	1.7	10	6	83.6
	HSC-S15	0.28	409	131.9	756	1,124	1.7	15	4	86.2

pressive strength. In the second test (test II), the linear expansion and the change in weight of concrete were used as a means for assessing the damage caused by the attack.

2.1. Effect of sulfate attack on compressive strength

Seven mixes (OPNSC, OPHSC, SFHSC, HSC-S0, HSC-S5, HSC-S10, and HSC-S15; see Table 1) were prepared to investigate the effect of sulfate attack on the compressive strength. About 720 cylindrical specimens of $\phi100 \times 200$ mm were produced. The OPNSC mix was a normal concrete without superplasticizer or silica fume with 0.54 water-binder (W/B) ratio, including silica fume, and had a 23-MPa compressive strength at the age of 28 days. Superplasticizer was added to the OPHSC and SFHSC mixes in order to obtain high strength. Silica fume (10% by weight of cement) was included in the SFHSC mix. The contents of cement and water were controlled so that these two mixes would have the same W/B ratio of 0.36. HSC-S0–HSC-S15 mixes were high strength concrete specimens with silica fume content in the range of 0 to 15%.

Fifty specimens for each mix were immersed in pure water, 10% sodium sulfate solution, 10% magnesium sulfate solution, and combined sulfate solution (mixed solution of 10% sodium sulfate and 10% magnesium sulfate). The cylinders were fully immersed in water and solutions in stainless steel baths. The cylinder was kept apart at a distance of 5 cm. The stainless steel baths were covered in order to minimize the evaporation. The solutions were replaced once a month with fresh ones and the pH was maintained at 7 during 270 days test.

Compressive strength test was performed for each mix in each solution at 60, 90, 120, 150, 210, and 270 days of immersion.

2.2. Effect of sulfate attack on expansion and weight loss

Four mixes (HSC-S0, HSC-S5, HSC-S10, and HSC-S15) were prepared to investigate the effect of sulfate attack on the linear expansion and the weight variation. Over 200 cube specimens of $50 \times 50 \times 50$ mm size were cast. These mix designs are featured by variable content of silica fume and superplasticizer. All the test specimens were immersed in pure water and the three kinds of sulfate solutions described in the preceding section.

The cube specimens were fully immersed in water and the solutions in the same way as test I. The dimension and

Table 2
Physical properties of mixture

Properties of coarse aggregate	Grading/Weight percentage passing (%)							
	25 mm	20 mm	10 mm	5 mm	2.5 mm	Fineness modulus	Percentage of solids (%)	
	100	98	28	1	1	6.72	56.0	
	Weight passing No. 200 sieve (%)	Abrasion (%)	Specific gravity of S.S.D.	Absorption (%)	Unit weight (kg/m^3)	Soundness (%)	Clay lumps (%)	
	0.5	13.9	2.73	1.18	1513	3.5	0.1	
Properties of fine aggregate	Fineness modulus	Specific gravity	Absorption	Clay lumps	Loss of washing	Organic impurities	Salt contamination	Soundness
	2.56	2.65	1.0	0.2	1.1	Good	0.0	Below 3
Properties of cement	Fineness (cm^2/kg)		Soundness (%)		Setting time (min)		Hydration heat (°C)	
					Initial set	Final set	7 days	28 days
	3.523		0.162		220	310	72.46	81.85

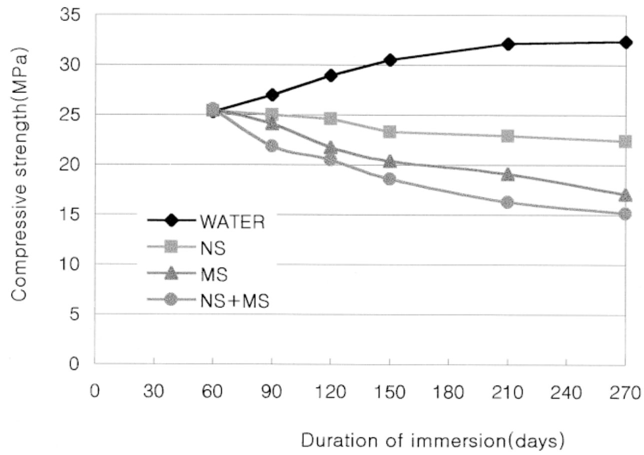

Fig. 1. Compressive strength of OPNSC.

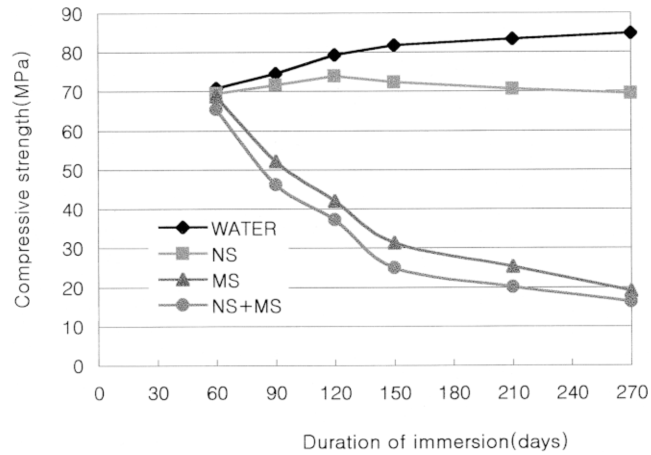

Fig. 3. Compressive strength of SFHSC.

the weight of the specimens were measured at the same immersion times as test I.

2.3. Properties of mixture and mixing procedure

Ordinary Portland cement (ASTM Type I) was used for all the specimens. The coarse aggregate was crushed material with a maximum size of 19 mm, and the fine aggregate was river sand. Powdered silica fume produced by Elkem Co. (Norway) was used in these tests. The physical properties of materials are given in Table 2.

Several mixing procedures were tried before producing the test specimens. The selected procedure was the one that was the most effective in maximizing the dispersion of silica fume particles and in minimizing the water absorption of aggregates after contact with water. The specimens were produced by ready-mixed concrete. All the materials were mixed in a batch through an agitator of ready-mixed concrete truck.

3. Results and discussion

3.1. Compressive strength

Fig. 1 shows the compressive strength variation of the normal strength concrete specimens without superplasticizer or silica fume (OPNSC). While the strength of the specimens in pure water increases with time, the strength of the specimens in sodium sulfate solution tends to decrease slightly (NS in Fig. 1). The strength of the specimens in magnesium sulfate solution (MS in Fig. 1) and combined sulfate solution (NS+MS in Fig. 1) shows a greater tendency to decrease than that of sodium sulfate solution.

The compressive strength variation of the high strength concrete specimens with superplasticizer (OPHSC in Fig. 2) is similar to that of OPNSC. However, the specimens in sodium sulfate solution tend to have a constant compressive strength, regardless of the duration of immersion time. It may be said that the increase in the compressive strength by continued hydration is balanced with the decrease due to the

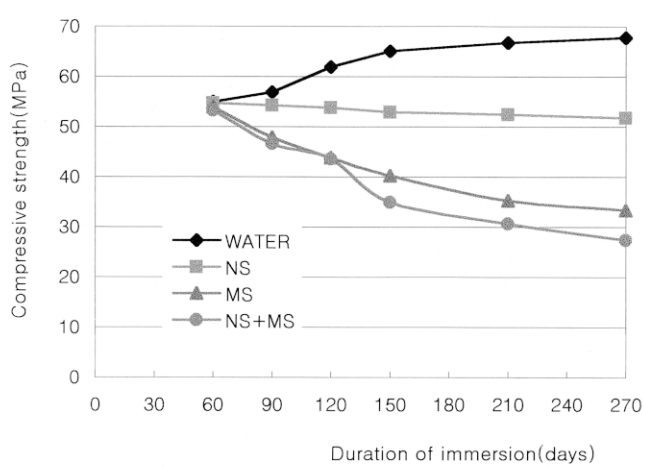

Fig. 2. Compressive strength of OPHSC.

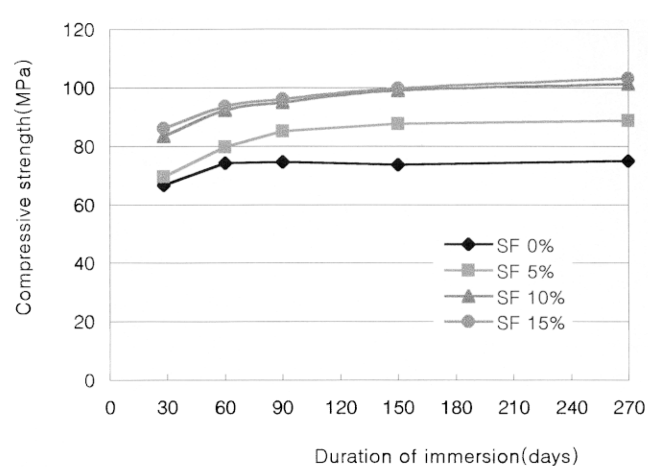

Fig. 4. Compressive strength of HSC-S0–HSC-S15 in pure water.

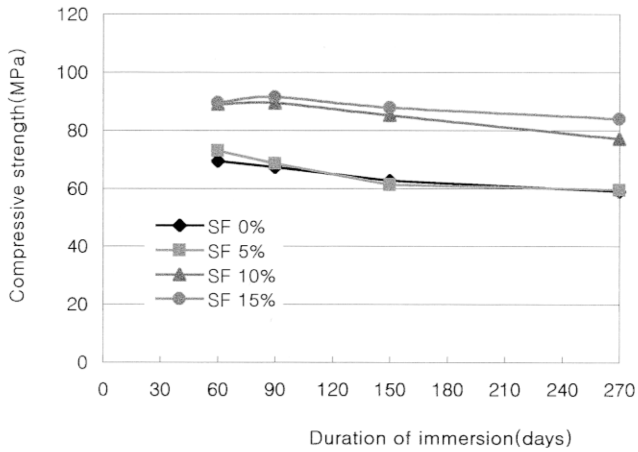

Fig. 5. Compressive strength of HSC-S0–HSC-S15 in sodium sulfate solution.

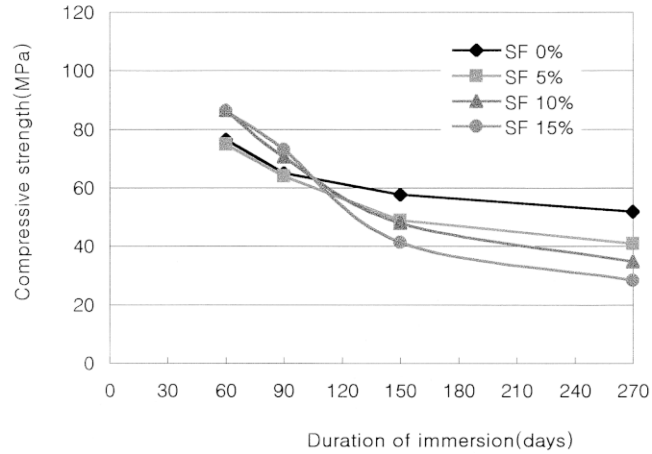

Fig. 7. Compressive strength of HSC-S0–HSC-S15 in combined sulfate solution.

sodium sulfate attack. The compressive strength variation of the high strength concrete specimens with superplasticizer and silica fume (SFHSC in Fig. 3) is similar to that of OPHSC, except that the specimens in magnesium sulfate solution and combined sulfate solution have a greater reduction in strength than that of OPHSC.

From the observation of the test results, it can be seen that the compressive strength of the specimens in pure water increases regardless of the mix proportions. However, as the immersion time is increased, the compressive strength of the specimens under the sulfate solutions tends to decrease and the rate of strength variation depends on the mix proportion and the type of sulfate solution. The compressive strength of the normal strength concrete specimens in sodium sulfate solution tends to decrease, while that of the high strength concrete specimens tends to be stable or slightly reduced. In magnesium sulfate solution and combined sulfate solution, the compressive strength variation shows a greater tendency for decrease than that in sodium sulfate solution.

Increase in silica fume is associated with higher strength in water immersion (Fig. 4). In sodium sulfate solution, the compressive strength of all the specimens has a tendency to decrease slightly (see Fig. 5). However, in magnesium sulfate solution the strength increases considerably, with a tendency for higher reduction for the higher silica fume contents (Figs. 6 and 7).

Figs. 8, 9, and 10 show the strength of the specimens under sulfate solutions, relative to the compressive strength of the specimens in pure water. In sodium sulfate solution, the relative strength of OPHSC and SFHSC (high strength concretes) is higher than that of OPNSC (normal strength concrete, see Fig. 8). Among the high strength concrete specimens, the relative strength of SFHSC, which contains silica fume, is greater than that of OPHSC, which does not contain silica fume. At 270 days of immersion in sodium sulfate solution, the relative strength ratios of OPNSC, OPHSC,

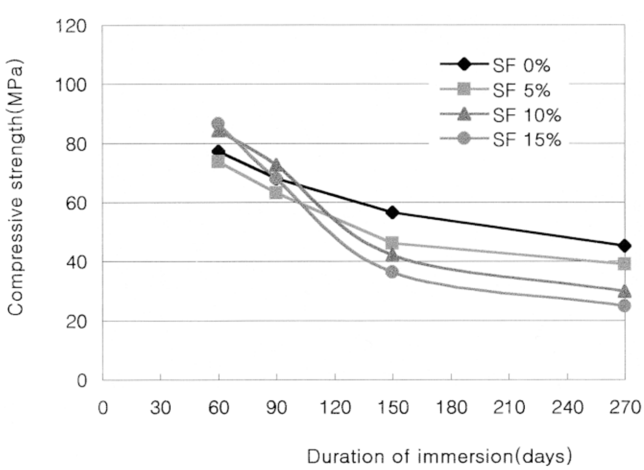

Fig. 6. Compressive strength of HSC-S0–HSC-S15 in magnesium sulfate solution.

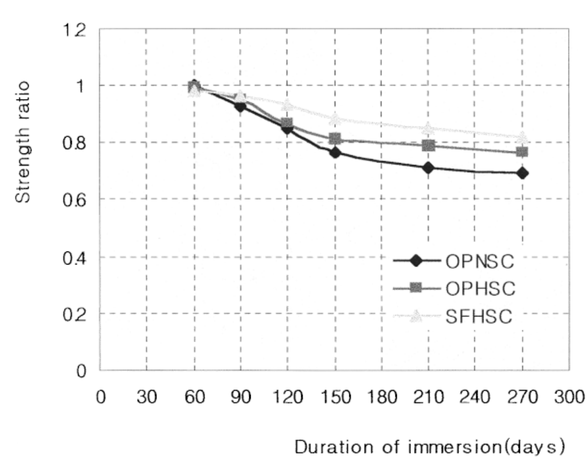

Fig. 8. Relative strength of concrete in sodium sulfate solution.

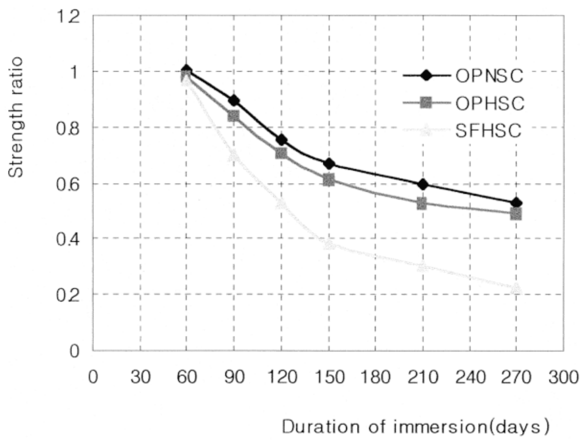

Fig. 9. Relative strength of concrete in magnesium sulfate solution.

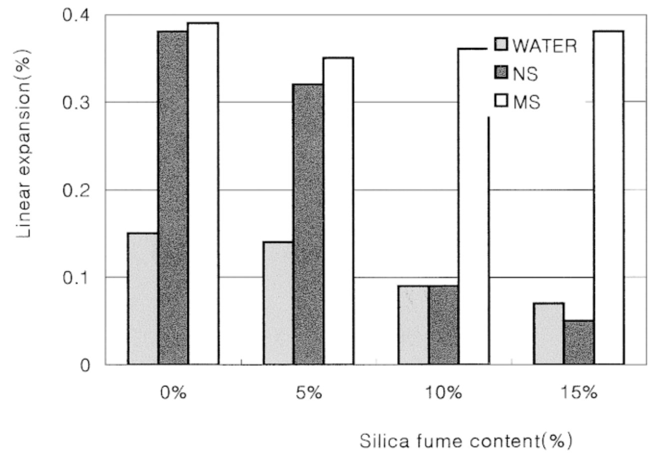

Fig. 11. Linear expansion of concrete at 150 days.

and SFHSC are 0.69, 0.76, and 0.82, respectively. In magnesium sulfate solution and combined sulfate solution, the relative strength shows the opposite trend with lower strength for the high silica fume mixes (see Figs. 9 and 10). The relative strength ratios of OPNSC, OPHSC, and SFHSC are 0.53, 0.49, and 0.23, respectively, after 270 days of immersion in magnesium sulfate solution.

This data indicates that the compressive strength of SFHSC is reduced by about 77% after 270 days of immersion compared with that of the concrete with the same mix proportion immersed in pure water. In combined sulfate solution, the relative strength of each mix shows the same tendency, as in the case of magnesium sulfate solution: At 270 days of immersion in combined sulfate solution, the relative strength ratios of OPNSC, OPHSC, and SFHSC are 0.47, 0.41, and 0.19, respectively.

3.2. Linear expansion and weight loss

The dimension and the weight of the cube specimens were measured at 150 days and at 270 days of immersion. Linear expansion values are compared with respect to the silica fume content and the type of solution in which the specimens were immersed.

Figs. 11 and 12 show that the linear expansion in water at 150 days decreases at higher silica fume contents, but no significant difference is seen at 270 days.

In sodium sulfate solution, the linear expansion is doubled at 150 days in the mixes without silica fume and with 5% silica fume content compared with the mixes in pure water. At 270 days, the linear expansion is greater than 1%, and is more than five times that of the specimens in pure water. The specimens with 10 and 15% silica fume content have very low linear expansion compared with the specimens of 5% silica fume content.

The specimens in magnesium sulfate solution show a different tendency in the linear expansion than the specimens in sodium sulfate solution. The linear expansion values do not show significant difference at 150 days; however, they significantly increase at 270 days for the higher silica fume content mixes. While the linear expansion of the specimens with 5% silica fume content are 0.19% in pure water, 1.1% in sodium sulfate solution, and 0.77% in magnesium sulfate

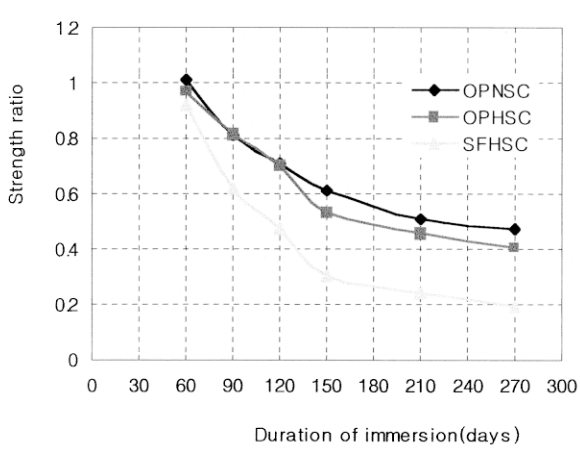

Fig. 10. Relative strength of concrete in combined sulfate solution.

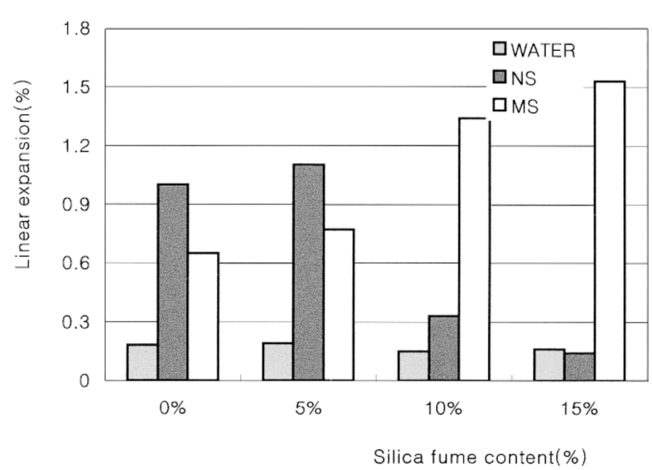

Fig. 12. Linear expansion of concrete at 270 days.

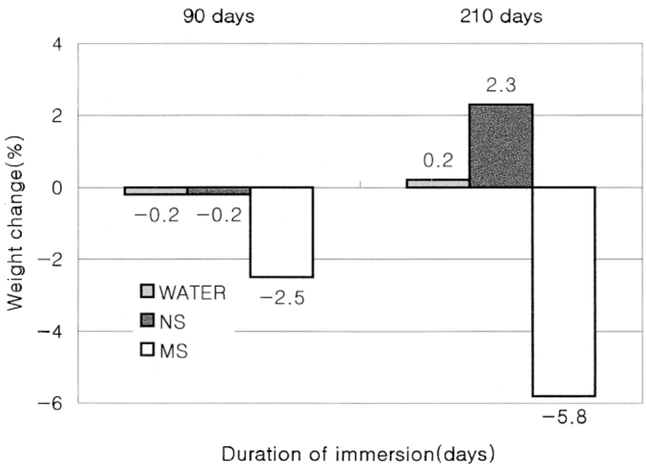

Fig. 13. Weight variations of high strength concrete specimens (without silica fume).

solution, the linear expansion of the specimens with 10% silica fume content are 0.15, 0.33, and 1.34%, respectively.

The weight variations of the specimens at an age of 90 days are negligibly small in pure water and in sodium sulfate solution, regardless of the silica fume content. There is a slight increase at 210 days (see Figs. 13 and 14). However, the weight of the specimens in magnesium sulfate solution decreases significantly. It can be also observed that the specimens with 15% silica fume content are affected much more by the magnesium sulfate solution: The weight of specimens without silica fume is reduced by 2.5% at 90 days and 5.8% at 210 days, while the weight of specimens with 15% silica fume content is reduced by 10.5% at 90 days and 20.7% at 210 days.

4. Conclusions

Laboratory tests were performed to determine the deterioration induced by the chemical attack of magnesium sulfate and sodium sulfate on normal and high strength concretes.

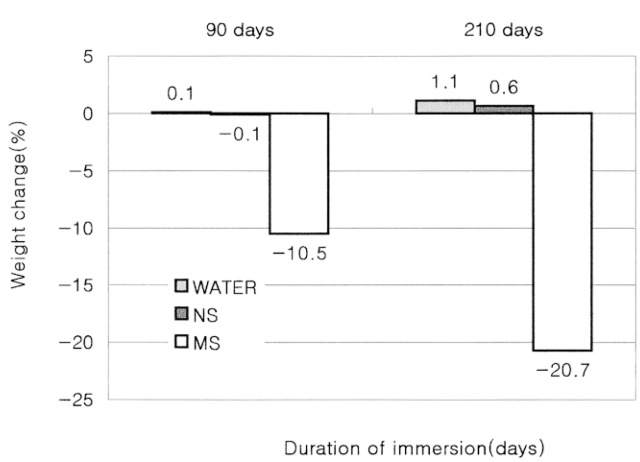

Fig. 14. Weight variations of high strength concrete specimens (15% silica fume content).

The selected solutions were pure water and 10% sulfate solutions, which were determined by consideration of the soil environment in Korea. The selected parameters in this study were water-binder ratio, silica fume content, and the compressive strength of concrete. The results of the tests are as follows:

1. Sodium sulfate and magnesium sulfate cause the deterioration of concrete; however, the magnesium sulfate has a greater effect on the reduction in compressive strength.
2. In sodium sulfate attack, the normal strength concrete specimens without superplasticizer or silica fume (OPNSC) have the poorest performance as seen by a greater tendency to decrease in the compressive strength. This may be due to the larger permeability associated with the higher water-cement ratio.
3. In magnesium sulfate attack, the high strength concrete specimens with superplasticizer and silica fume (SFHSC) show the poorest performance as seen by the tendency to decrease in the compressive strength. This means that although the high strength concrete with silica fume is the most efficient against sodium sulfate attack, its resistance to magnesium sulfate attack decreases as the content of silica fume increases. The specimens that contain at least 10% silica fume (HSC-S10 and HSC-S15) have less strength than the specimens that used less than 10% silica fume (HSC-S0 and HSC-S5) after 270 days.
4. In higher silica fume mixes, less linear expansion occurs in sodium sulfate solution, but more linear expansion occurs in magnesium sulfate solution.
5. The weight variation of the specimens at an age of 90 days is negligibly small in pure water and in sodium sulfate solution regardless of the silica fume content. However, the weight of the specimens in magnesium sulfate solution is significantly decreased in particular mixes with 15% silica fume content.

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