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Sulfate resistance of plain and blended cements exposed to varying concentrations of sodium sulfate

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Abstract

Concrete deterioration due to sulfate attack is the second major durability problem, after reinforcement corrosion. This type of deterioration is noted in the structures exposed to sulfate-bearing soils and groundwater. Though concrete deterioration due to sulfate attack is reported from many countries, the mechanisms of sulfate attack have not been thoroughly investigated, particularly the effect of sulfate concentration and the cation type associated with the sulfate ions on concrete deterioration. This study was conducted to evaluate the performance of plain and blended cements exposed to varying concentrations of sodium sulfate for up to 24 months. Four types of cements, namely Type I, Type V, Type I plus silica fume and Type I plus fly ash, were exposed to five sodium sulfate solutions with sulfate concentrations of 1%, 1.5%, 2%, 2.5% and 4%. These concentrations are representative of the sulfate concentration in highly saline soils. The sulfate resistance was evaluated by visual examination and measuring the and reduction in compressive strength. The maximum deterioration, due to sulfate attack, was noted in Type I cement followed by silica fume and Type V cements. The performance of Type V, Type I plus silica fume and Type I plus fly ash was not significantly different from each other. The enhanced sulfate resistance noted in the Type I cement blended with either silica fume or fly ash indicates the usefulness of these cements in both sulfate and sulfate plus chloride environments.

Keywords: Blended cements; Plain cements; Sodium sulfate; Sulfate attack; Strength reduction; Visual inspection

1. Introduction

Sulfate ions in soil, ground water, and sea water cause deterioration of reinforced concrete structures due to sulfate attack. In hardened cement, C_3A reacts with sulfate ions in the presence of calcium hydroxide to form ettringite and gypsum, leading to degradation of concrete into a non-cohesive granular mass and disruptive expansion [1–4].

Research related to concrete deterioration due to sulfate attack resulted in the development of the sulfate resisting Type V cement [1–4]. However, the chemical composition of ordinary portland cements has undergone several changes resulting in a significant increase in the C_3S content to achieve a rapid development of strength [1–4]. This change renders concrete prepared with even Type V cement vulnerable to sulfate attack for two reasons. Firstly, with modern cements, it is possible to achieve higher 28-day strength using a leaner mix with a higher water/cement ratio resulting in a relatively open pore structure and hence a permeable concrete. Secondly, an increase in the C_3S content of cement generates a significantly higher amount of calcium hydroxide (CH), as a byproduct of hydration, resulting in a gypsum-oriented sulfate attack characterized by softening of the cement matrix. This position has lead to a closer examination of the possibility of utilizing supplementary cementing materials, such as silica fume and fly ash, for enhancing the sulfate resistance of cements. The superior performance of blended cements over plain cements in decreasing the sulfate deterioration of concrete is primarily attributed to the pozzalnic reaction, which consumes the deleterious CH, and to the dilution of the C_3A phase due to a reduction in the quantity of cement.

Sulfate attack on concrete is a complex process as was reported by Cohen and Mather [5]. Many factors, such as cement type, sulfate cation type, sulfate concentration

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and exposure period, may affect the sulfate resistance. However, not much research has been conducted to evaluate the effect of sulfate concentration on the performance of plain and blended cements [6,7]. ACI 318 and BS 8110 and other codes of practices provide guidelines on the quality of concrete and the type of cement to be used for varying sulfate concentrations. However, these need to be updated due to the fact that cement chemistry has undergone several changes over the years and that supplementary cementing materials, particularly silica fume, are increasingly used worldwide these days in concrete. Moreover, these guidelines are specific for sulfate concentrations of less than 10,000 ppm while higher sulfate concentrations of up to 22,000 ppm are noted in certain saline soils [8].

In this study, the performance of plain and blended cements when exposed to high sulfate concentrations was evaluated.

2. Experimental procedures

2.1. Materials

The sulfate resistance of four cements, namely Type I, Type V, Type I plus silica fume and Type I plus fly ash, when exposed to high sulfate concentrations, was evaluated. In the silica fume cement, 7% silica fume was used as a replacement of cement. The fly ash cement contained 20% fly ash. Tables 1–3 summarize the properties of portland cement and the supplementary cementing materials utilized to prepare the specimens.

Cement mortar specimens, measuring 50 × 50 × 50 mm, were prepared by mixing the selected cements with dune sand. The sand to cementitious materials ratio in the mortar mixes was 2.5 and the water to cementitious materials ratio was 0.5.

Table 1
Chemical composition of plain cements

Constituent (wt.%)	Type V	Type I
SiO_2	22.00	20.52
Al_2O_3	4.08	5.64
Fe_2O_3	4.24	3.80
CaO	64.07	64.35
MgO	2.21	2.11
SO_3	1.96	2.10
Loss on ignition	0.80	0.70
K_2O	0.31	0.36
Na_2O	0.21	0.19
Na_2O equivalent	0.41	0.43
C_3S	54.57	56.70
C_2S	21.91	16.05
C_3A	3.64	8.52
C_4AF	12.90	11.56

Table 2
Characteristics of silica fume

Property	Test results	ASTM C 1240 requirements
Moisture content, %	1.35	3.0 max.
Loss on ignition, %	1.62	6.0 max.
SiO_2, %	98.0	85 min.
Fe_2O_3, %	2.73	–
Al_2O_3, %	0.70	–
CaO, %	0.12	–
MgO, %	0.67	–
Na_2O, %	0.39	–
K_2O, %	0.90	–
Material retained on # 325 sieve, %	2.01	10 max.
Specific surface area, m^2/g	16.7	15 min.
Accelerated pozzolanic activity index, % (7 days)	98	85%
Shrinkage (Type I cement after 28 days), %	0.069	–
Shrinkage (Type I + silica fume cement after 28 days), %	0.099	–
Increase over control, %	0.030	0.1 max.
Sulfate-resistance expansion (6 months), %	0.048	0.05 max. (high resistance)

Table 3
Characteristics of fly ash

Property	Value
Moisture content, %	<0.1
Loss on ignition, %	0.8
SiO_2, %	52.8
Fe_2O_3, %	3.5
Al_2O_3, %	34.3
CaO, %	4.4
MgO, %	1.1
Na_2O, %	0.4
K_2O, %	0.5
P_2O_5, %	0.3
SO_3, %	0.1
Material retained on # 325 sieve, %	9.5
Water requirement, % of control	90.0
Reactivity, MPa	10.0

2.2. Specimens

Cement mortar specimens, 50 × 50 × 50 mm, were prepared from each of the selected cements. Deionized water was used in these mixtures. The constituents were mixed in a laboratory mortar mixer till uniform consistency was obtained. In the blended cements, the pozzolanic materials were first thoroughly mixed with the cement and then deionized water was added. The mortar was poured into the molds that were vibrated on a vibrating table to remove the entrapped air. After casting and finishing, the molds were covered with plastic sheets and kept under laboratory conditions for 24 h and then demolded. After demolding, the specimens were cured under water maintained at 23 °C for further 27 days.

2.3. Exposure and testing

After 28 days of curing, the mortar specimens were divided into two groups. One group of specimens was continuously cured under water while the second group was placed in four tanks with the following sulfate concentrations:

(i) 1% SO_4^{-2} (10,000 mg/l),
(ii) 1.5% SO_4^{-2} (15,000 mg/l),
(iii) 2% SO_4^{-2} (20,000 mg/l),
(iv) 2.5% SO_4^{-2} (25,000 mg/l),
(v) 4% SO_4^{-2} (40,000 mg/l).

The above exposure conditions represent very severe sulfate exposure conditions according to ACI 318-99. However, these concentrations represent the sulfate concentrations noted in saline soils, denoted as sabkha, that are widely prevalent in many parts of the world [8,9].

The exposure solutions were prepared by mixing reagent grade sodium sulfate with distilled water. Sixteen specimens representing similar composition were placed in each solution for up to 24 months. The concentration of the solution was checked periodically and the solution was changed every 4 months.

Three mortar specimens representing similar composition were retrieved from the test solutions after 4, 8, 15 and 24 months of exposure. The effect of sulfate concentration on the performance of plain and blended cements was evaluated by visual examination and measuring the reduction in compressive strength. The mortar specimens were inspected after the designated exposure period and the deterioration was classified on a six point scale ranging from 0 to 5 [8]. A rating of 0 would indicate no deterioration while a rating of 5 indicates complete failure.

The degree of deterioration was also evaluated by measuring the reduction in compressive strength. The reduction in compressive strength was calculated as follows:

$$\text{Reduction in compressive strength, \%} = [(A - B)/(A)] \times 100,$$

where A is the average compressive strength of three specimens cured under water, MPa; and B is the average compressive strength of three specimens exposed to the test solution, MPa.

3. Results

Figs. 1–5 show plain and blended cement mortar specimens exposed to 1%, 1.5%, 2%, 2.5% and 4% SO_4^{-2} solutions for 24 months. As is evident in Fig. 1, cracking was noted in Type I cement mortar specimens while minor spalling was noted in the silica fume cement

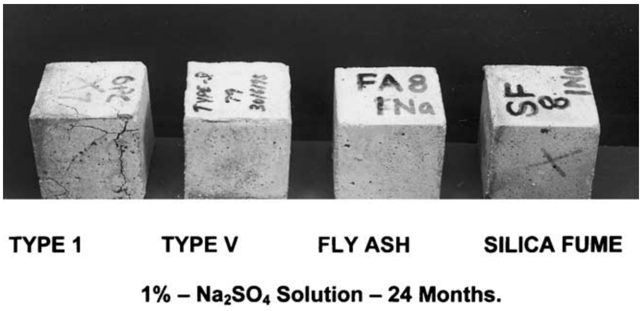

Fig. 1. Plain and blended cement mortar specimens exposed to 1% sulfate solution for 24 months.

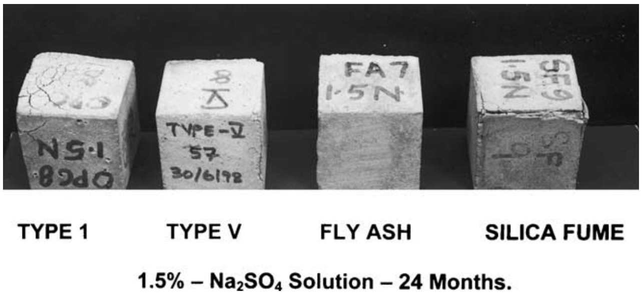

Fig. 2. Plain and blended cement mortar specimens exposed to 1.5% sulfate solution for 24 months.

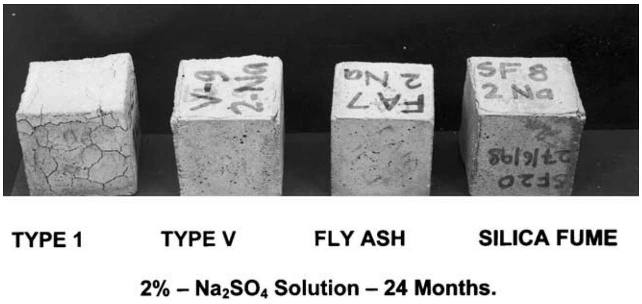

Fig. 3. Plain and blended cement mortar specimens exposed to 2% sulfate solution for 24 months.

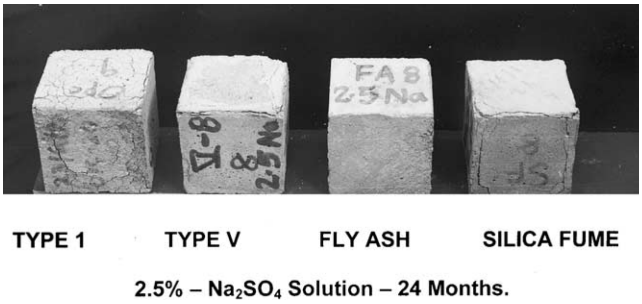

Fig. 4. Plain and blended cement mortar specimens exposed to 2.5% sulfate solution for 24 months.

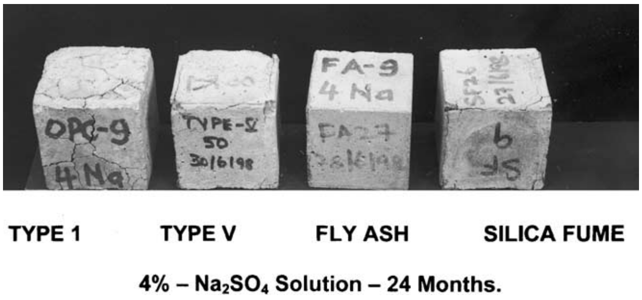

Fig. 5. Plain and blended cement mortar specimens exposed to 4% sulfate solution for 24 months.

mortar specimens. Cracking was also evident in Type I cement mortar specimens exposed to 1.5% sulfate solution while spalling of the surface skin, localized at the edges, was noted in Type V and silica fume cement mortar specimens. No damage was noted in the fly ash cement mortar specimens. The severity of spalling was more intense in the silica fume cement mortar specimens compared to Type V cement mortar specimens. In the specimens exposed to 2% and 2.5% sulfate solution, the deterioration was more severe in Type I cement mortar specimens compared to other cements. While marginal deterioration was noted in the silica fume and Type V cements, no wear and tear was observed in the fly ash cement mortar specimens. Similar behavior was noted in the plain and blended cement mortar specimens exposed to 4% sulfate solution. The severity of deterioration in Type I, Type V and silica fume cement mortar specimens exposed to 4% sulfate solution was, however, more than that in the specimens exposed to the solutions with lower sulfate concentrations. This trend was particularly noted in the Type I cement mortar specimens.

Table 4 shows the deterioration rating for the plain and blended cement mortar specimens exposed to 1% sulfate solution. The deterioration increased with the period of exposure in all the specimens. However, early deterioration, i.e., after 8 months, was noted in the Type I cement mortar specimens. After 24 months of exposure, a deterioration rating of 3 was assigned to Type I cement while the deterioration rating was 1 for Type V, silica fume and fly ash cement mortar specimens.

The deterioration ratings for the cement mortar specimens exposed to 1.5% sulfate solution are summarized in Table 5. In this group of specimens also severe deterioration was noted in Type I cement mortar specimens compared to silica fume, Type V and fly ash cement mortar specimens, in the decreasing order. Tables 6–8 show the deterioration ratings for plain and blended cement mortar specimens exposed to 2%, 2.5% and 4% sulfate solution. A higher deterioration rating was assigned to Type I cement. The deterioration rating was the highest for Type I cement mortar specimens, followed by silica fume, Type V and fly ash cements, in the decreasing order. Further, a comparison of deterioration ratings summarized in Tables 4–8 indicates that

Table 4
Deterioration rating for specimens exposed to 1% sulfate solution

Cement	Sample #	Deterioration rating (months)			
		4	8	15	24
Type I	1	0	1	2	3
	2	0	1	2	3
	3	0	1	2	3
Type V	1	0	0	0	1
	2	0	0	1	1
	3	0	0	1	1
Type I + 7% silica fume	1	0	0	1	1
	2	0	0	1	1
	3	0	0	1	1
Type I + 20% fly ash	1	0	0	0	1
	2	0	0	0	1
	3	0	0	0	1

Table 5
Deterioration rating for specimens exposed to 1.5% sulfate solution

Cement	Sample #	Deterioration rating (months)			
		4	8	15	24
Type I	1	1	2	3	4
	2	1	2	3	4
	3	1	2	3	4
Type V	1	0	0	0	2
	2	0	0	0	2
	3	0	0	0	2
Type I + 7% silica fume	1	0	0	1	2
	2	0	0	1	3
	3	0	0	1	3
Type I + 20% fly ash	1	0	0	0	1
	2	0	0	0	1
	3	0	0	0	1

Table 6
Deterioration rating for specimens exposed to 2% sulfate solution

Cement	Sample #	Deterioration rating (months)			
		4	8	15	24
Type I	1	2	2	3	4
	2	2	2	3	4
	3	2	2	3	4
Type V	1	0	0	0	2
	2	0	0	0	2
	3	0	0	0	2
Type I + 7% silica fume	1	0	0	1	2
	2	0	0	1	3
	3	0	0	1	3
Type I + 20% fly ash	1	0	0	0	1
	2	0	0	0	1
	3	0	0	0	1

Table 7
Deterioration rating for specimens exposed to 2.5% sulfate solution

Cement	Sample #	Deterioration rating (months)			
		4	8	15	24
Type I	1	2	2	3	4
	2	2	2	3	4
	3	2	2	3	4
Type V	1	0	0	1	2
	2	0	0	1	2
	3	0	0	1	2
Type I + 7% silica fume	1	0	0	1	3
	2	0	0	1	3
	3	0	0	1	3
Type I + 20% fly ash	1	0	0	1	1
	2	0	0	1	1
	3	0	0	1	1

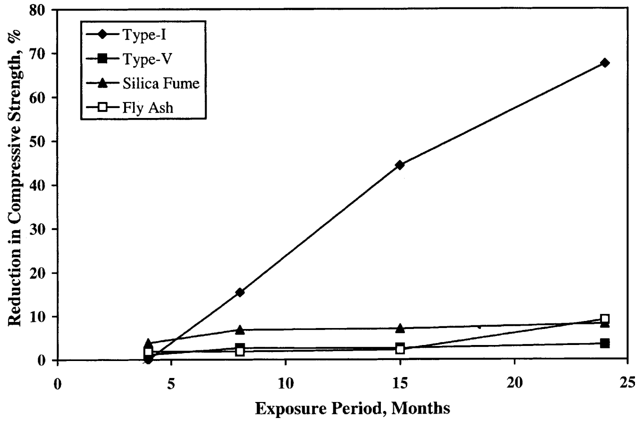

Fig. 6. Reduction in compressive strength of mortar specimens exposed to 1% SO_4^{-2} solution.

Table 8
Deterioration rating for specimens exposed to 4% sulfate solution

Cement	Sample #	Deterioration rating after (months)			
		4	8	15	24
Type I	1	3	4	4	4
	2	3	4	4	4
	3	3	4	4	4
Type V	1	1	1	1	3
	2	1	1	1	3
	3	1	1	1	3
Type I + 7% silica fume	1	1	2	2	3
	2	1	2	2	3
	3	1	2	2	3
Type I + 20% fly ash	1	0	1	2	2
	2	0	1	2	2
	3	0	1	2	2

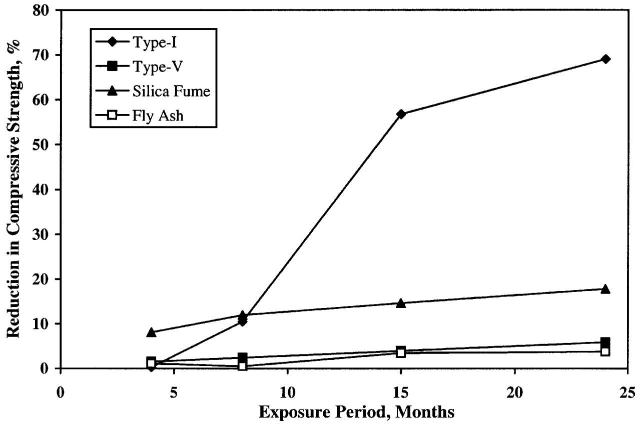

Fig. 7. Reduction in compressive strength of mortar specimens exposed to 1.5% SO_4^{-2} solution.

the rate of deterioration increased with increasing sulfate concentration in both plain and blended cements.

The reduction in compressive strength of plain and blended cements due to exposure to 1% sulfate solution is depicted in Fig. 6. A linear decrease in strength, with the period of exposure, was noted in the Type I cement mortar specimens while the strength reduction in Type V, silica fume and fly ash cement mortar specimens was almost similar and did not increase with the period of exposure. Further, a large variation in strength reduction was noted between Type I cement and the other cements investigated in this study. The reduction in compressive strength in the plain and blended cements exposed to 1.5% sulfate solution are plotted in Fig. 7. A higher strength reduction was also noted in Type I cement mortar specimens. Further, the strength reduction in the silica fume cement mortar specimens was more than that in Type V and fly ash cements. The strength reduction in the latter two cements was almost similar. A substantial variation between the strength reduction in the Type I and other plain and blended cements was also noted in this group of specimens. This trend was particularly apparent after 8 months of exposure.

The strength reduction in the plain and blended cements exposed to 2%, 2.5% and 4% SO_4^{-2} solutions is plotted in Figs. 8–10. A higher strength reduction was noted in Type I cement mortar specimens while the strength reduction in other cements was not significantly different from each other.

The strength reduction in the plain and blended cements after 24 months of exposure to 1%, 1.5%, 2%, 2.5% and 4% sulfate solutions is depicted in Figs. 6–10. After 24 months of exposure to the sulfate solutions the reduction in strength, due to sulfate attack, was the highest in Type I cement. Also, the reduction in strength in Type I cement was almost similar for all the concentrations. However, in other cements, the reduction in

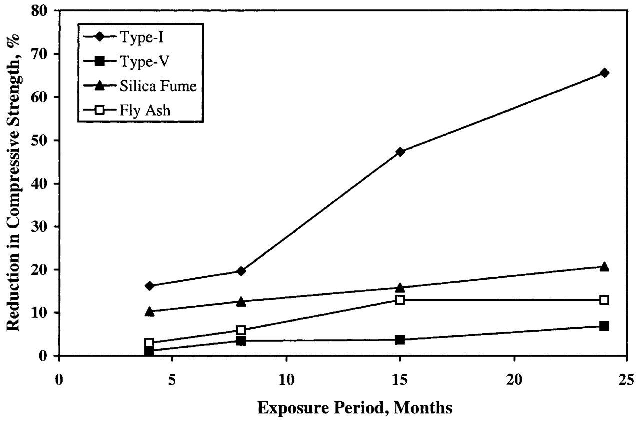

Fig. 8. Reduction in compressive strength of mortar specimens exposed to 2% SO_4^{-2} solution.

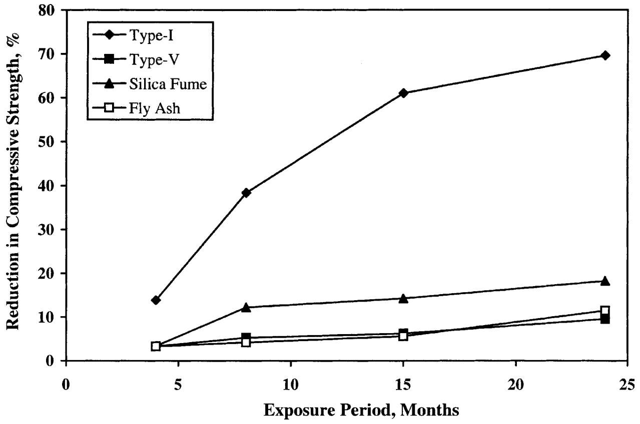

Fig. 9. Reduction in compressive strength of mortar specimens exposed to 2.5% SO_4^{-2} solution.

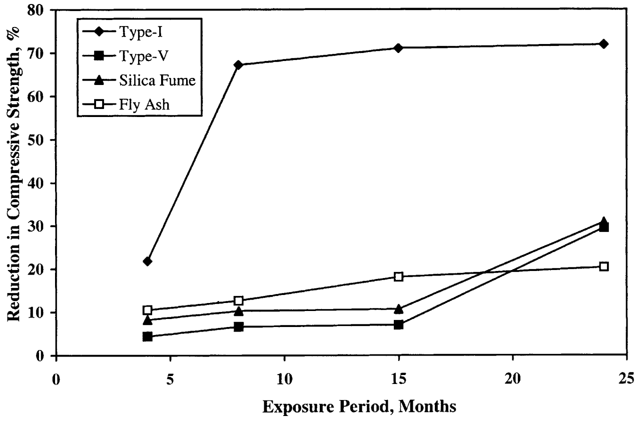

Fig. 10. Reduction in compressive strength of mortar specimens exposed to 4% SO_4^{-2} solution.

strength was influenced by the concentration of the sulfate solution, though the change was not that significant.

4. Discussion

The data reported in this paper indicate that the type of cement has a significant effect on the sulfate attack. Type I cement blended with 20% fly ash exhibited the best resistance to sulfate attack, followed by Type V cement and Type I plus 7% silica fume. The maximum deterioration was noted in the Type I cement mortar specimens. As shown in Fig. 11, the strength reduction in Type I cement after 24 months of exposure was almost similar for all the sulfate concentrations. However, the rate of deterioration in Type V, fly ash and silica fume cements increased with increasing sulfate concentration. The visual examination of the specimens during 24 months of exposure also revealed considerable deterioration, in the form of cracking, in Type I cement mortar specimens. Deterioration in the form of spalling of the skin at the corners was noted in Type V and silica fume cement mortar specimens. The extent of deterioration in the silica fume cement mortar specimens was more than that in Type V cement mortar specimens. No deterioration of any sort was noted in the fly ash cement mortar specimens even after 24 months of exposure to 4% sulfate solution.

As shown in Figs. 1–5, the mode of failure in Type I cement mortar specimens was mainly due to the formation of expansive cracking. This type of failure is typical of the sodium sulfate attack in moderate to high C_3A cements [1–4]. Expansive reaction takes place when excessive hydrated aluminate phases present in the cement react with the sulfate ions in the presence of calcium hydroxide. This reaction leads to the formation of tricalcium sulfoaluminate hydrate, known as ettringite, which is expansive in nature.

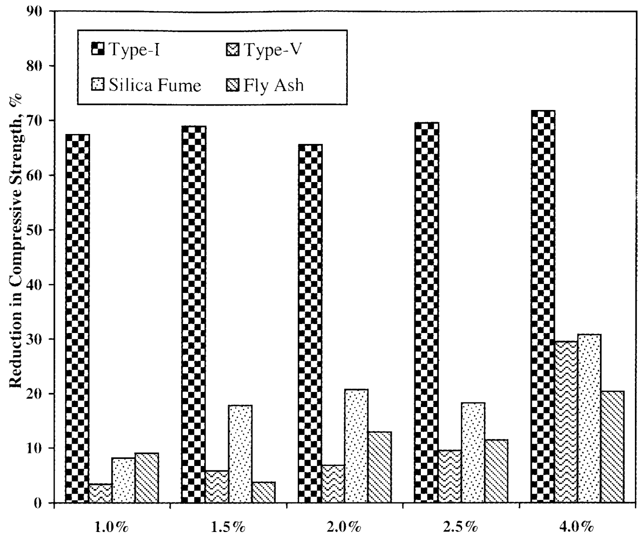

Fig. 11. Comparison of reduction in compressive strength in the mortar specimens exposed to varying concentrations of sodium solution for 24 months.

Deterioration of concrete due to the chemical reaction between the hydrated Portland cement and sulfate ions is known to take two forms depending on the concentration and the type of sulfate ions (the associated cation) and the composition of cement paste in concrete. The first type of sulfate attack usually manifests in the form of expansion of concrete leading to its cracking. The second type of sulfate attack takes the form of a progressive loss of strength and mass due to deterioration in the cohesiveness of the hydrated cement.

Among the hydration products, calcium hydroxide and alumina-bearing phases are more vulnerable to attack by sulfate ions. On hydration, Portland cements with more than 5% C_3A contain most of the alumina in the form of monosulfate hydrate, $C_3A.C\overline{S}.H_{18}$. If the C_3A content of the cement is more than 8%, the hydration products also contain $C_3A.CH.H_{18}$. In the presence of calcium hydroxide, when the cement paste comes in contact with sulfate ions, both the alumina-containing hydrates are converted to ettringite ($C_3A.3C\overline{S}.H_{32}$) [1].

The formation of ettringite generates excessive expansion in concrete. However, the mechanisms by which ettringite formation causes expansion is still a subject of controversy. Exertion of pressure (≅240 MPa) by forming ettringite crystals and swelling due to adsorption of water in an alkaline environment by poorly crystalline ettringite, are two of the several hypotheses that are supported by most researchers [10].

Therefore, realizing the role of C_3A on sulfate attack, cements of low C_3A are recommended in situations where the substructural components are exposed to sulfate environments. However, cements with low C_3A generally have a higher C_3S/C_2S. An increase in the C_3S content of cement generates a significantly higher amount of calcium hydroxide. Calcium hydroxide can also react directly with the sulfate ions leading to the formation of gypsum. The deterioration of hardened Portland cement paste by gypsum formation goes through a process leading to a reduction of stiffness and strength; this is followed by expansion and cracking, and eventual transformation of the material into a mushy or non-cohesive mass. In cements with high C_3A, such as ASTM C 150 Type II and Type I cements, exposed to sodium sulfate environments, ettringite formation leading to expansion and cracking is the major form of concrete deterioration [2]. This type of deterioration leads to a drastic reduction in the strength as against gypsum formation noted in the low C_3A Type V cement.

Rasheeduzzafar et al. [11] investigated the influence of cement composition on sulfate resistance of cements with varying C_3A content of cement and indicated that in addition to the C_3A content, the C_3S to C_2S ratio has a significant influence on the sulfate resistance. They investigated on the sulfate resistance of two Type I cements with C_3A contents of 11.9% and 9.3%. It was reported that the C_3S to C_2S ratio for the cement with higher C_3A was 7.88 whereas it was 2.57 for the lower C_3A cement. After 150 days of accelerated sulfate exposure, Type I cement with higher C_3A was found to have deterioration that was 2.5 times higher than that for the Type I Portland cement with lower C_3A content. Significant retrogression of strength was observed on immersion in a sulfate solution even in a Type V (C_3A: 1.88%) cement that had a C_3S to C_2S ratio of 5.28. On the other hand, 20% silica fume blended with a Type I cement with a 14% C_3A content performed 1.4 times better than a Type V cement with a C_3A content of 1.88%.

The improved performance of Type V cement in resisting sulfate attack may be attributed to the low C_3A (3.5%) content in this cement, as explained earlier. The lower expansion in the fly ash and silica fume cements may be attributed to both a reduction in the quantity of C_3A and calcium hydroxide. When pozzolanic materials are added to cement, they react with calcium hydroxide in the presence of moisture to form secondary calcium silicate hydrate. The secondary calcium silicate hydrate formed due to the pozzolanic reaction is similar in essence to the primary C–S–H produced by the hydration of Portland cement itself although the former is less dense than the latter [2]. The pozzolanic action leads to the consumption of portlandite that reduces the formation of gypsum. The replacement of part of the cement by a pozzolanic material also entails a reduction in the C_3A content. Hence, all the aluminate-bearing phases will accordingly be reduced. Therefore, the formation of ettringite will be mitigated. Since blended cements consume a significant portion of the calcium hydroxide produced by the hydration of cement and reduce the pH, the ettringite becomes less expansive. The secondary C–S–H also forms a film or a coating on the alumina-rich and other reactive phases thereby hindering the formation of ettringite. The formation of secondary C–S–H also results in the densification of the hardened cement paste since it is deposited in the pores thereby making blended cements impermeable and, therefore, sulfate ions cannot easily diffuse through the concrete matrix.

The slightly elevated deterioration noted in the silica fume cement mortar specimens compared to the fly ash cement mortar specimens may be attributed to the reduction in the quantity of calcium hydroxide in the latter cement due to a higher replacement (20%) of cement. The higher replacement of cement dilutes the quantity of both the C_3A and calcium hydroxide that are essential for the sulfate attack to proceed. It is also possible that the fly ash utilized in the preparation of mortar specimens is more reactive than the silica fume.

Another implication of the improved performance of Type I cement blended with either silica fume or fly ash is the usefulness of this cement in environments containing both chloride and sulfate salts. In such environments, a cement with a C_3A content of more than 5% is required for chloride-binding, even though such a cement may be harmful from sulfate attack point of view. The addition of pozzolanic materials to Type I cement provides similar performance rating as Type V cement in terms of sulfate attack. Therefore, the use of Type I cement in conjunction with a suitably characterized pozzolanic material can enhance the durability of concrete by increasing its resistance to reinforcement corrosion and sulfate attack. Further, the incorporation of pozzolanic materials in cements leads to a reduction in the cost of cement where they are available locally.

Another aspect that was the focal point of this study was the effect of sulfate concentration on the sulfate resistance of plain and blended cements. The effect of sulfate concentration on concrete deterioration due to sulfate attack was more apparent in Type I cement, than in Type V or blended cements. In the earlier stages, the severity of deterioration increased with the sulfate concentration. However, after 24 months of exposure, the extent of deterioration in Type I cement was almost similar irrespective of the sulfate concentration, as is evident from the strength reduction data presented in Figs. 1–5. Furthermore, the concentration of the sulfate solutions had an insignificant effect on the sulfate resistance of Type V, silica fume and fly ash cements. Cracking of concrete was noted in Type I cement while spalling of the surface skin at the edges, representative of the acidic attack due to the formation of gypsum, was noted in Type V cement and Type I cement blended with silica fume. The higher strength reduction noted in Type I cement, compared to Type V, silica fume and fly ash cements, may be attributed to the formation of cracks in the former cement while etching of the surface skin in the latter cements had an insignificant effect on their strength. In summary, the data developed in this study indicate that sulfate attack under high sulfate concentrations is significantly influenced by the type of cement.

ACI 318 specifies moderately sulfate-resistant Type II, similar to Type I cement investigated in this study, or modified cement, such as IP(MS), IS(MS), P(MS), I(PM)(MS), or I(MS) for moderate sulfate (150–1500 ppm) exposure. For severe (1500–10,000 ppm) and very severe (over 10,000 ppm) sulfate exposures, Type V and Type V plus pozzolanic cement, respectively, are recommended. The data developed in this study have indicated that Type V and Type I cements blended with fly ash or silica fume provide sufficient sulfate resistance under severe and very severe sulfate exposure. While Type V cement provides the required sulfate resistance for severe and very severe sulfate exposures, blending of Type I cement with a properly characterized supplementary cementing material has the advantage that it will be resistant to sulfate attack and offer better corrosion protection to the reinforcing steel compared to Type V cement alone. Therefore, Type I cement blended with a pozzolanic material is recommended for high sulfate plus chloride exposures. The selected pozzolanic material should meet the relevant ASTM standards or it should be proved by service records to improve the sulfate resistance.

5. Conclusions

Significant deterioration was noted in the Type I cement mortar specimens, while it was marginal in Type V and silica fume cement mortar specimens. Deterioration in the Type I cement was manifested in the form of cracks while etching of the surface skin was noted in Type V cement and Type I cement blended with silica fume. No deterioration of any sort was noted in Type I cement blended with fly ash.

The maximum strength reduction, due to sulfate attack, was noted in Type I cement mortar specimens while it was the lowest in Type V cement mortar specimens. The reduction in strength in the silica fume and fly ash cement mortar specimens was not significantly different from that of Type V cement.

The strength reduction in Type V cement and Type I cement blended with either silica fume or fly ash increased with the concentration of the sulfate solution while the sulfate concentration had an insignificant effect on Type I cement mortar specimens.

Since the performance of Type I cement blended with either silica fume or fly ash was similar to Type V cement, it is recommended to utilize blended cements in concrete to improve the concrete durability in terms of both sulfate attack and reinforcement corrosion.

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References

[1] Rasheeduzzafar, Al-Amoudi OSB, Abduljawad SN, Maslehuddin M. Magnesium–sodium sulfate attack in plain and blended cements. J Mater Civil Eng 1994;6(2):201–22.

[2] Al-Amoudi OSB, Maslehuddin M, Saadi MM. Effect of magnesium sulfate sodium on the durability performance of plain and blended cements. ACI Mater J 1955;92(1):15–24.

[3] Al-Amoudi OSB. Performance of 15 reinforced concrete mixtures in magnesium and sodium sulfate environments. Construct Build Mater J 1995;9(3):149–58.

[4] Al-Amoudi OSB. Sulfate attack and reinforcement corrosion in plain and blended cements exposed to sulfate environments. Build Environ 1998;33(1):53–61.

[5] Cohen MD, Mather B. Sulfate attack on concrete-research needs. ACI Mater J 1991;88(1):62–9.

[6] Fevziye A, Fikret T, Sema K, Nabi Y. Effects of sodium sulfate concentration on the sulfate resistance of mortars with and without silica fume. Cem Concr Res 1995;25(6):1360–8.

[7] Fikret T, Fevziye A, Sema K, Nabi Y. Effects of magnesium sulfate concentration on the sulfate resistance of mortars with and without silica fume. Cem Concr Res 1997;27(2):205–14.

[8] Al-Amoudi OSB, Rasheeduzzafar, Maslehuddin M, Abduljawad SN. Influence of chloride ions on sulphate deterioration in plain and blended cements. Mag Concr Res 1994;46(167):113–23.

[9] Al-Amoudi OSB, Abduljauwad SN, Rasheeduzzafar, Maslehuddin M. Effect of chloride and sulfate contamination in soils on corrosion of steel and concrete. Transport Res Rec 1992;1345: 67–73.

[10] Cohen MD, Bentur A. Durability of portland cement-silica fume pastes in magnesium sulfate and sodium sulfate solutions. ACI Mater J 1988;85(3):148–57.

[11] Rasheeduzzafar, Dakhil FH, Al-Gahtani AS, Sadoun SS, Bader MA. Influence of cement composition on the corrosion of reinforcement and sulfate resistance of concrete. ACI Mater J 1990;87(2):112–4.