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STRENGTH LOSS IN CONCRETE DUE TO VARYING SULFATE EXPOSURES

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ABSTRACT

The paper presents the results of an experimental study in which the loss in strength of concrete exposed to time varying sulfate environments is determined. A measure of cumulative damage to the material under time dependent exposure conditions is introduced. The test data indicate that the cumulative damage, when concrete is exposed to a succession of sulfate solutions of varying concentrations over successive time intervals, is dependent on the order of application of the exposure.

1. Introduction

Considerable attention is given to the effect of sulfate attack on cement based building materials, in view of its practical importance. Sulfate environments influence strength, safety, serviceability, ductility, durability, aesthetics and economy of structures made with cement concrete and other materials. Inspite of the efforts to develop special cements and other techniques of resisting sulfate attack, studies on influence of sulfates with the ordinary portland cement continue to be of interest, because of several reasons. As a consequence of pollution, for example, sulfate attack can occur on an existing structure with ordinary portland cement. The studies will also help in establishing norms when special cements will be economical alternatives to the ordinary portland cement.

Most of the existing studies on the influence of sulfates on the strength of concrete (1-5) focussed attention on strength deterioration when exposed to constant sulfate ion exposure over a time interval. The results have been very valuable. Nevertheless, in actual practice, structures are exposed to environmental influences which vary with time. Hence what is of interest is the quantification of strength loss and damage under time varying exposure histories. It is the object of this investigation to study the deterioration in strength of concrete when subjected to sulfate attack, the degree of attack being a time dependent variable.

2. Experimental Programme

Usually in situations where sulfate environments are anticipated, relatively richer mixes with low water-cement ratios are adopted. This aspect is kept in mind in planning the experimental programme. Three grades of concrete designated as mix A, mix B and mix C were adopted in this investigation. The details of the mixes are given in Table 1. Coarse aggregate of maximum size 20 mm, and fineness modulus 7.12, river sand of fineness modulus 2.36 as fine aggregate and ordinary portland cement were used in making concretes with the mixes A, B and C. The water-cement ratio was kept constant in all the mixes.

TABLE 1

Details of Concrete Mixes

Mix	Mix Ratio (by weight) Cement : Sand : Coarse Aggregate	Water-Cement Ratio
A	1 : 2 : 4	0.5
B	1 : 1.5 : 3	0.5
C	1 : 1 : 2	0.5

The actual variation of strength with time in the three mixes is shown in Figure 1, mix B gave the highest, followed by A and C.

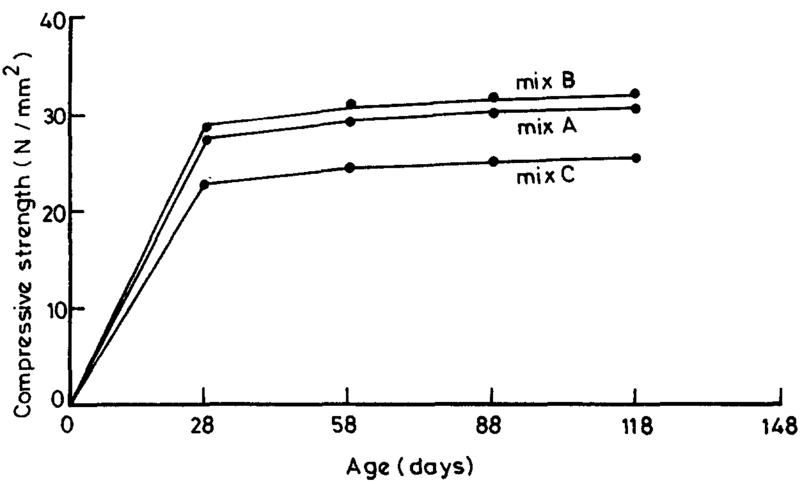


FIG. 1

Variation of Concrete Strength with Age in Fresh Water

Sodium sulfate was chosen as it is among the most widely occurring sulfates in practice. In most practical situations, concentrations of sulfates (SO_4^{-}) in ground waters and soils are upto the order of 1000 ppm (6), while those of sea water and industrial effluents are more. Thus, the range of practical importance of the sulfate concentrations (SO_4^{-}) is between 150 and 6000 ppm when the attack on unprotected concrete is studied (7). In the present study, sulfate concentrations were taken equal to 500, 2000 and 5000 ppm. The quantity of sodium sulfate (Na_2SO_4) added to the water for making the sulfate solution with sulfate concentration (SO_4^{--}) equal to 1000 ppm was 1.48 gm/litre.

In the present study an estimate is made of the damage when concrete is subjected to a succession of environmental histories in terms of time dependent sulfate concentrations. Concrete cubes were cast and cured for 118 days in sodium sulfate solutions (Na_2SO_4), the concentrations of which varied with time as shown in Table 2. In total, the effect of six different exposure histories was studied on concrete cubes made with the three mixes. In Table 2, A_1 for example, denotes cubes with concrete mix A and exposure history 1. The six histories of exposure were adopted with various combinations of ion concentrations which are representative of the degree of sulfate attack. For example, the first exposure history in Table 2 indicates that the concrete cubes after 28 days curing in fresh water are subjected to 30 days curing in sulfate solution of ion concentration 500 ppm, for further 30 days in sulfate solution of 2000 ppm and for another 30 days cured in sulfate solution of concentration 5000 ppm. Other exposure histories can be similarly interpreted. The cubes, in all the cases, were tested at a rate of 14 $N/mm^2/min$ to get the compressive strength.

3. Experimental Results and Discussion

By damage to a material exposed to an aggressive environment like sulfates, one means the development of several undesirable characteristics like loss of strength, loss of elasticity, permanent deformation, decolourization etc. All these are undesirable from the technical point of view. Thus damage is a summative phenomenon implying the total effect of many individual deterioration processes; it is naturally difficult to give a general definition and quantitative measure of damage. Often, loss in strength is a quantity of primary interest and is one important measure of degree of attack.

The precentage damage, D is defined as

$$D = (1 - \frac{\sigma_R}{\sigma}) \times 100 \qquad (1)$$

where

σ_R = strength after exposure to sulfate environment for a period of T, and

σ = strength in the absence of sulfate environment after time T, where T is the curing period in days.

Thus, D = 0 if $\sigma_R = \sigma$, that is no damage and when D = 100, $\sigma_R = 0$, implying complete strength loss.

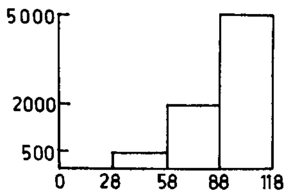
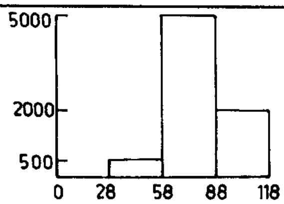
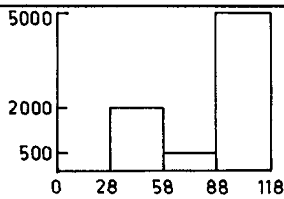
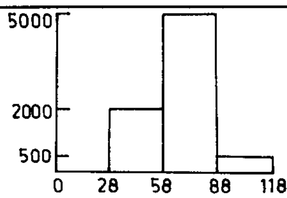
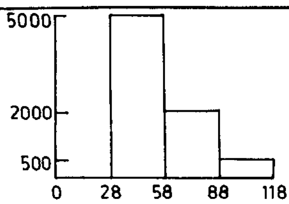
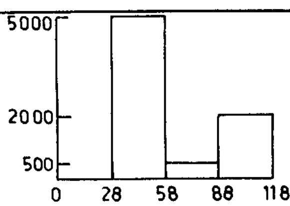
The value of D in each case is given in Table 3 for all the exposure histories and the mixes A, B and C.

Considering the total damage given in Table 3, in all the three grades of concrete, after exposure to varying sulfate concentrations as shown in Table 2, it can be observed that the damage is dependent on the order of application of the successive exposures. The variation in the magnitude of the damage is within 15-20 percent. Table 3 shows that the concrete subjected to a higher sulfate concentration in initial days of curing has more damage as compared to concrete subjected to a sulfate solution of low concentrations initially.

It can also be seen that the damage in compressive strength increases with the period of exposure and a concrete with higher strength has less damage in strength when exposed to time varying sulfate exposure.

TABLE 2

Sulfate Exposure Histories of Concrete Cubes

S.No.	Sulfate Exposure	Mix Designation		
		A	B	C
①		A_1	B_1	C_1
②		A_2	B_2	C_2
③		A_3	B_3	C_3
④		A_4	B_4	C_4
⑤		A_5	B_5	C_5
⑥		A_6	B_6	C_6

NOTE: THE SULFATE ION ($SO_4^{=}$) CONCENTRATION IN ppm IS GIVEN ON THE ORDINATE AND THE EXPOSURE DURATION IN DAYS ON THE ABSISSA

TABLE 3

Percentage Damage, D in Compressive Strength of Concrete

Mix	Mix Designation and Exposure History	Damage		
		58 day	88 day	118 day
A	A_1	2.24	3.62	5.71
	A_2	2.24	6.05	7.14
	A_3	5.22	5.35	6.43
	A_4	5.22	5.81	7.14
	A_5	6.51	6.94	7.57
	A_6	6.51	6.51	7.43
B	B_1	1.69	3.46	5.14
	B_2	1.69	5.33	5.71
	B_3	2.42	3.69	5.84
	B_4	2.42	5.32	6.51
	B_5	3.80	6.51	6.97
	B_6	3.80	5.57	6.25
C	C_1	2.82	5.84	7.50
	C_2	2.82	7.01	8.37
	C_3	4.67	5.84	7.60
	C_4	4.67	7.01	8.73
	C_5	6.51	7.89	8.96
	C_6	6.51	7.60	8.73

Comparing the behaviour of mixes A, B and C as given in Table 2, it can be seen that the concrete with mix B has the least damage; this indicates the feasibility of the existance of an optimum aggregate-cement ratio for best resistance against sulfate attack.

The possible reasons for the observed behaviour of concretes under sulfate attack are as given in the following (8-12).

1. The environmental sulfate ions react with crystalline calcium hydroxide present in the hydrated cement to yield crystalline gypsum, given by equation 2.

$$2\ Na^{+} + SO_4^{--} + Ca(OH)_2 + 2\ H_2O \longrightarrow 2\ Na^{+} + 2\ OH^{-} + CaSO_4.2H_2O \qquad (2)$$

2. The sulfate ions react with hydrated aluminates to form ettringite. The relation can be given in the abbreviated form as follows :

$$C_3A.C\bar{S}.H_{18} + 2\ N\bar{S} + 2\ CH + 14\ H \longrightarrow C_3A.3\ C\bar{S}.H_{32} + 2\ NH \qquad (3)$$

$$C_3A.CH.H_{18} + 3\ N\bar{S} + 2\ CH + 14\ H \longrightarrow C_3A.3\ C\bar{S}.H_{32} + 3\ NH \qquad (4)$$

Regarding sodium sulfate attack, the corrosive mechanism depends on the sulfate ion concentration (6). At low concentrations (SO_4^{--} concentrations of less than 1000 ppm, this limit changes with change in C_3A content of portland cement) the mechanism causing damage to concrete is by ettringite formation. When sulfate concentration is higher, the mechanism is dominated by gypsum formation. There is a transition range where these two formations overlap.

As a consequence of the sulfate attack, loss in compressive strength is caused by both internal expansion due to the formation of ettringite and gypsum and by leaching of calcium hydroxide. The progressive formation of gypsum at the expense of the cementitious constituents normally present in the hydrated cement paste, causes loss of strength. As a consequence of sulfate attack, concrete is rendered relatively porous and weak and eventually reduces to a noncohesive mass.

4. Conclusions

Based on the experimental study the following conclusions are drawn.

1. The damage to concrete is dependent on the order of application of the successive sulfate exposures. The variation in damage is within 15-20 percent.
2. The damage to concrete exposed to higher sulfate concentrations in the beginning is more as compared to concrete exposed to low sulfate concentrations initially.
3. A concrete mix having higher value of strength shows less damage in strength when exposed to a time varying sulfate exposure.

Further investigations of the strength behaviour and cumulative damage when concrete is subjected to a higher number of successive exposures to aggressive chemicals of varying intensities and duration are under progress and the results will be reported in due course.

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