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Chloride-induced reinforcement corrosion in blended cement concretes exposed to chloride-sulphate environments

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This paper reports the results of a study conducted to investigate the influence of sulphate concentration and associated cation type on chloride-induced reinforcement corrosion in blended cement concretes. Reinforced concrete specimens were exposed to chloride plus sulphate solutions for a period of 1200 days. The exposure solutions contained a fixed concentration of 5% sodium chloride and the sulphate concentration was varied from 0 to 4% SO_4^{2-} . The effect of cation type associated with sulphate ions, namely Na^+ and Mg^{++} , on chloride-induced reinforcement corrosion was also evaluated. Reinforcement corrosion was assessed by measuring corrosion potentials and corrosion current density at regular intervals. The results indicated that the presence of sulphate ions in the chloride solution increased the corrosion current density, but no significant effect on the time to initiation of reinforcement corrosion was noted. Further, the corrosion current density increased with increasing sulphate concentration and the period of exposure. The corrosion current density on steel in the blended cement concrete specimens was much less than that in the plain cement concrete specimens, indicating that the corrosion resistance of blended cements was much better than that of plain cements. The cation type associated with sulphate ions did not significantly influence either the initiation or rate of reinforcement corrosion.

Introduction

Deterioration of concrete structures due to reinforcement corrosion is a major problem facing the construction industry worldwide. Reinforcement corrosion is caused either by chloride ions or carbonation, although chloride-induced reinforcement corrosion is the more widespread and serious problem. The chloride ions may be introduced into concrete at the time of mixing through admixtures, aggregates and mix water. Alternatively, they may diffuse into the hardened concrete from the service environment. Curing of concrete with saline water also introduces chloride ions to the steel surface. The practice of curing concrete with saline water is common in countries where the desalinated water is costly.

Concrete structures in marine environments and below ground conditions are exposed to several other salts in addition to chloride ions. Some of the salts, such as sulphates, affect concrete durability. The sulphate salts are known to affect concrete durability by reacting with the cement hydration products. Further, sulphate ions may affect chloride-induced reinforcement corrosion firstly by reacting with C_3A thereby reducing the chloride-binding capacity of cement and second by the formation of gypsum or calcium sulphoaluminate which leads to cracking or softening of the concrete cover.

The precise role of sulphate ions on the mechanisms of chloride-induced reinforcement corrosion is, however, not known. Limited data developed by Al-Amoudi *et al.*¹⁻⁴ indicated that sulphate ions significantly influence the rate of chloride-induced reinforcement corrosion. In those studies only two sulphate concentrations (0.55 and 2.1%) were investigated. Further, the required concentrations of sulphate ions were obtained by mixing equivalent quantities of sodium sulphate and magnesium sulphate. Due to this mixing, the effect of cation type associated with the sulphate ions on reinforcement corrosion could not be assessed. In another

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study Maslehuddin *et al.*⁵ evaluated the effect of exposure temperature and sulphate contamination on chloride-induced reinforcement corrosion. According to the authors, the corrosion activity increased two to six times due to an increase in the temperature from 25 to 70°C. The increase in the corrosion activity due to the concurrent presence of chloride and sulphate salts was reported to be 1.1 to 2.4 times that measured in the concrete specimens contaminated with sodium chloride only.

As stated earlier, limited studies have been conducted to evaluate the effect of sulphate ions on chloride-induced reinforcement corrosion. Further, concrete exposed to magnesium sulphate is known to undergo significant deterioration, in terms of surface scaling^{6,7} thereby reducing the cover over the reinforcing steel and increasing the possibility of reinforcement corrosion. Therefore, there is a need to evaluate the effect of sulphate concentration and associated cation type on chloride-induced reinforcement corrosion. This study was conducted to assess the effect of sulphate concentration and the associated cation type on chloride-induced reinforcement corrosion in blended cement concretes.

Methodology of research

Materials and specimen preparation

Four cements, namely Portland cement (PC; C₃A: 8.5%), blast furnace slag (BFS), silica fume (SF) and fly ash (FA) were used to prepare reinforced concrete specimens. In the FA cement concrete specimens, 20% FA was used as a replacement of PC. In the silica fume cement concrete specimens, 10% PC was replaced with silica fume while blast furnace slag cement concrete specimens contained 70% BFS and 30% PC. The chemical composition of PC and pozzolanic materials is shown in Table 1.

Reinforced concrete cylindrical specimens, 75 mm in diameter and 150 mm high, were cast using concrete with an effective water to cementitious materials ratio (w/c) of 0.45 and total cementitious materials content of 350 kg/m³. The coarse aggregate was 1116 kg/m³ of crushed dolomitic limestone (with a specific gravity of 2.43 and water absorption of 2.3%) and the fine aggregate 684 kg/m³ of dune sand (with a specific gravity of 2.53 and water absorption of 0.57%). The coarse and fine aggregates were washed to remove all salts, dust and other fine particles. The volume of water in each mix was adjusted to compensate for the absorption of coarse and fine aggregates. All the concrete mixtures were designed for a workability of 50 to 75 mm slump. In the silica fume cement concrete, suitable dosage of a high-range water reducer was used to obtain the desired workability and an additional mixing time of 2 min was provided. The compressive strength of the concrete specimens was in the range 45–48 MPa.

Table 1. Composition of cements and supplementary cementing materials

Constituent: wt %	PC*	BFS†	SF‡	FA§
SiO ₂	20.52	35.40	92.50	49.72
Al ₂ O ₃	5.64	7.80	0.40	47.58
Fe ₂ O ₃	3.80	0.52	0.40	1.28
CaO	64.35	43.7	0.50	0.48
MgO	2.11	8.50	0.90	0.30
SO ₃	2.10	1.13	0.50	0.20
Loss on ignition	0.70	—	—	—
K ₂ O	0.36	—	—	—
Na ₂ O	0.19	—	—	—
Na ₂ O equivalent	0.43	—	—	—
C ₃ S	56.70	—	—	—
C ₂ S	16.05	—	—	—
C ₃ A	8.52	—	—	—
C ₄ AF	11.56	—	—	—

* Portland cement (C₃A: 8.5%).

† Blast furnace slag.

‡ Silica fume.

§ Fly ash.

The steel bars were cleaned and coated with cement paste followed by an epoxy coating at the concrete–air interface and the bottom of the bar in order to avoid crevice corrosion at these locations. The steel bars were cleaned with a silicon carbide paper, wherever necessary, and degreased with acetone prior to casting of the concrete specimens. The concrete specimens were cast in steel moulds. Before casting, the moulds were cleaned and slightly oiled to facilitate the demoulding process. A 12 mm diameter carbon steel bar was then fixed centrally at the middle of the mould providing a 25 mm clear cover at the bottom.

The concrete ingredients were mixed in a mechanical mixer and placed in the moulds in two layers by consolidation on a vibrating table. After casting, the specimens were covered with polyethylene sheets and allowed to cure at the laboratory temperature for 24 h. The specimens were then demoulded and cured in potable water maintained at 25°C for 27 days. After this curing period, the specimens were dried by keeping them at room temperature for one week and then placed in plastic containers containing the exposure solutions. This drying phase produced a more realistic moisture state. The excessive moisture in a near saturated concrete would also have produced very negative potential values.

Exposure

The concrete specimens were exposed to seven solutions with fixed chloride and varying sulphate concentrations as detailed in Table 2. All the solutions contained 5% NaCl and varying concentrations of sodium or magnesium sulphate. The sulphate concentration was varied from 0 to 4% to evaluate the effect of these ions on reinforcement corrosion. Three reinforced concrete specimens representing each concrete mix

Table 2. Composition of the exposure solutions

Group	Concentration of the exposure solution
1	5% NaCl
2	5% NaCl + 1% SO ₄ ²⁻ (Na ₂ SO ₄)
3	5% NaCl + 2.5% SO ₄ ²⁻ (Na ₂ SO ₄)
4	5% NaCl + 4% SO ₄ ²⁻ (Na ₂ SO ₄)
5	5% NaCl + 1% SO ₄ ²⁻ (MgSO ₄)
6	5% NaCl + 2.5% SO ₄ ²⁻ (MgSO ₄)
7	5% NaCl + 4% SO ₄ ²⁻ (MgSO ₄)

were placed in each of the exposure solutions. The concentration of the exposure solutions was monitored and adjusted fortnightly.

Monitoring of reinforcement corrosion

Reinforcement corrosion was evaluated by measuring corrosion potentials and corrosion current density (I_{corr}) at regular intervals. Reinforced concrete specimens were partially immersed in the exposure solution. The level of the solution was adjusted, so that only 85–90 mm of the bottom of the specimen was in the solution. The exposed steel area was 1500 mm². Measurements were conducted on three specimens representing similar mix composition and average values are reported.

The corrosion potentials were measured using a saturated calomel reference electrode (SCE) and a high impedance voltmeter.

The corrosion current density was evaluated by the linear polarisation resistance method. To determine the corrosion current density, the steel bar in the concrete specimen, a stainless steel frame (counter electrode) and a saturated calomel reference electrode were connected to an EG&G PAR Model 350 Potentiostat/Galvanostat. The steel was potentiodynamically polarised to ± 20 mV of the corrosion potential. A scan rate of 0.1 mV/s was used. The corrosion current density was then calculated using the following formula proposed by Stern and Geary⁸

$$I_{\text{corr}} = B/R_p$$

where I_{corr} is the corrosion current density, $\mu\text{A}/\text{cm}^2$; and R_p is the polarisation resistance, $\text{k}\Omega \cdot \text{cm}^2$

$$B = \frac{\beta_a \beta_c}{2.3(\beta_a + \beta_c)}$$

where β_a and β_c are the anodic and cathodic Tafel constants, mV/decade, respectively.

The Tafel constants are normally obtained by polarising the steel to ± 250 mV of the corrosion potential (Tafel plot). However, in the absence of sufficient data on β_a and β_c , a value of B equal to 26 mV for steel in an active condition and 52 mV for steel in a passive condition are normally used.⁹ In this investigation, Tafel constants of 120 mV/decade were used to determine the corrosion current density. In another study,

Dehwah *et al.*¹⁰ conducted Tafel experiments on reinforced concrete specimens and the values of Tafel constants were noted to be approximately 120 mV/decade. Lambert *et al.*¹¹ reported a good correlation between corrosion rate determined using these values and the gravimetric weight loss. The measured corrosion current density was corrected for the IR drop between the reference electrode and the steel bar by the positive feedback technique.

Results

Corrosion potentials

The corrosion potentials were measured on three replicate specimens and the average values are reported. The coefficient of variation in the three readings was within acceptable limits (<5%). The corrosion potentials on steel in the BFS cement concrete specimens exposed to 5% NaCl solutions admixed with sodium sulphate are plotted in Fig. 1. The corrosion potentials in these specimens decreased with the period of exposure. Fig. 2 depicts the variation of corrosion potentials on steel in the BFS cement concrete specimens exposed to 5% NaCl solution admixed with magnesium sulphate. The corrosion potentials on steel in these cement concrete specimens were either less than -270 mV SCE right from the initial stages of exposure, or a drastic reduction in the corrosion potentials was noted after one week of exposure.

The corrosion potentials on steel in the SF cement concrete specimens exposed to 5% NaCl solutions admixed with sodium sulphate are plotted against period of exposure in Fig. 3. The corrosion potentials were high during the initial stages of exposure. However, a sharp decrease was noted up to 210 days of exposure, beyond which the potentials were more or less the same. Fig. 4 shows the corrosion potentials on steel in the SF cement concrete specimens exposed to 5% NaCl

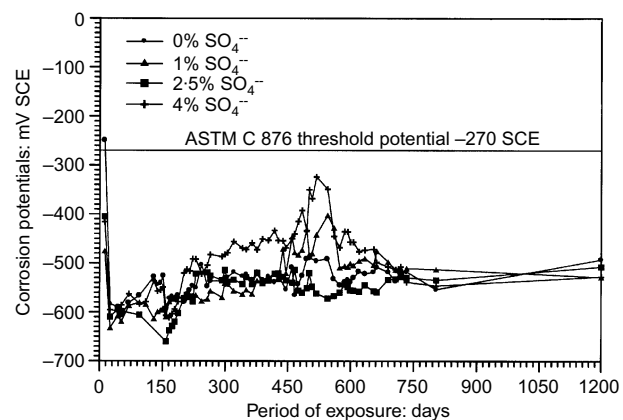


Fig. 1. Corrosion potentials on steel bars in the BFS cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

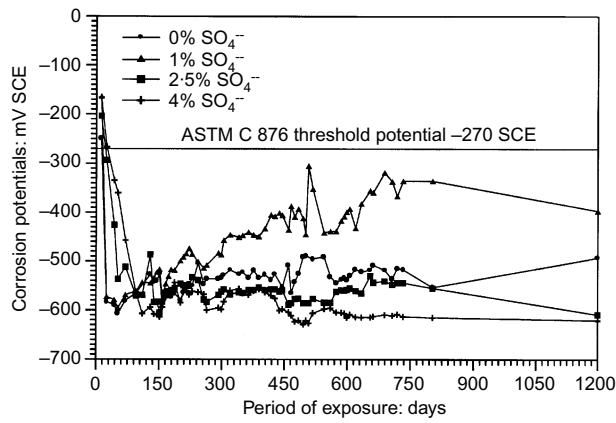


Fig. 2. Corrosion potentials on steel in the BFS cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

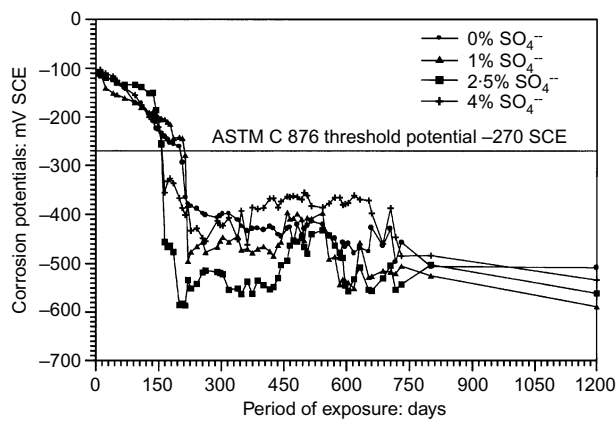


Fig. 3. Corrosion potentials on steel bars in the SF cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

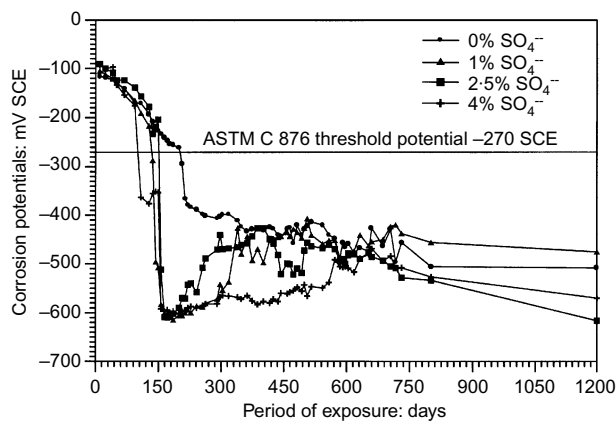


Fig. 4. Corrosion potentials on steel in the SF cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

solutions admixed with magnesium sulphate. Initially, the corrosion potentials were high and thereafter decreased sharply up to an exposure period of 190 days and they were stable at later times.

The corrosion potentials on steel in the FA cement

concrete specimens exposed to 5% NaCl solutions admixed with sodium sulphate are plotted against time of exposure in Fig. 5. The corrosion potentials decreased with time and were stable after about 150 days. Fig. 6 shows the corrosion potentials on steel in the FA cement concrete specimens exposed to 5% NaCl solutions admixed with magnesium sulphate. The corrosion potentials in these specimens initially decreased with the period of exposure and were stable at later times.

The corrosion potentials on steel in the PC (C₃A: 8:5%) concrete specimens exposed to 5% NaCl solution admixed with 0, 1, 2.5 and 4% SO₄²⁻, derived from sodium sulphate, are plotted against the period of exposure in Fig. 7. Initially, the corrosion potentials were high (less negative) and decreased with the period of exposure. However, after 180 days of exposure, the corrosion potentials tended to be stable in all the specimens. The corrosion potentials on the steel in the PC concrete specimens exposed to sodium chloride plus magnesium sulphate solutions are plotted in Fig. 8. The

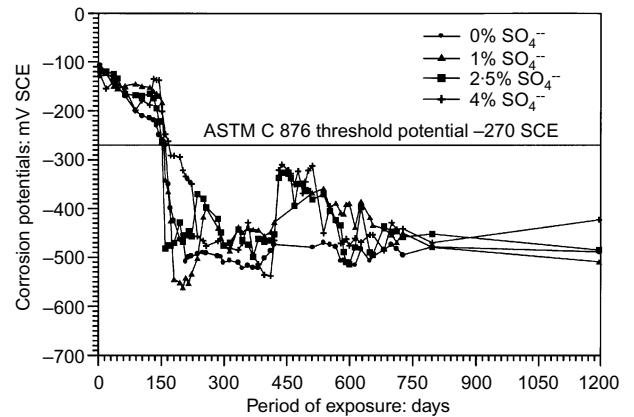


Fig. 5. Corrosion potentials on steel bars in the FA cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

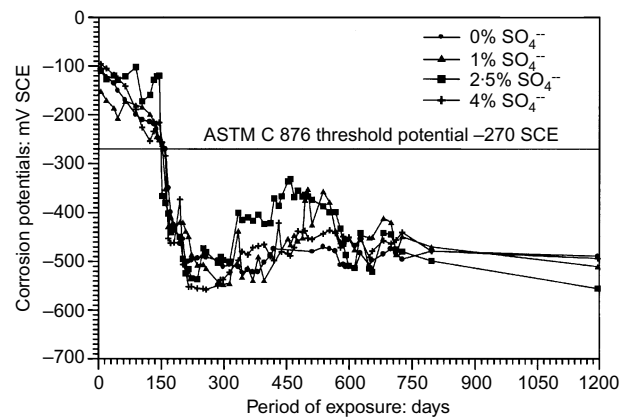


Fig. 6. Corrosion potentials on steel in the FA cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

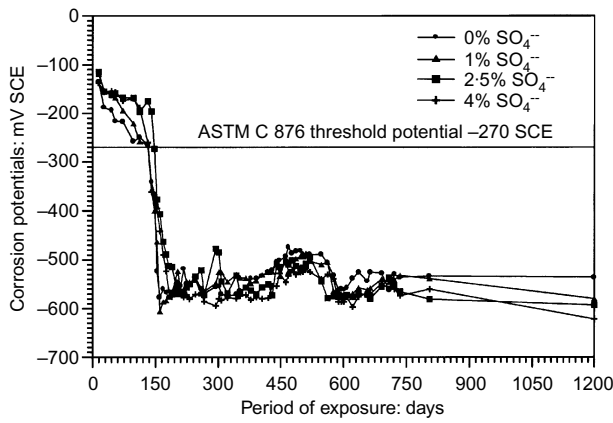


Fig. 7. Corrosion potentials on steel bars in the PC concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

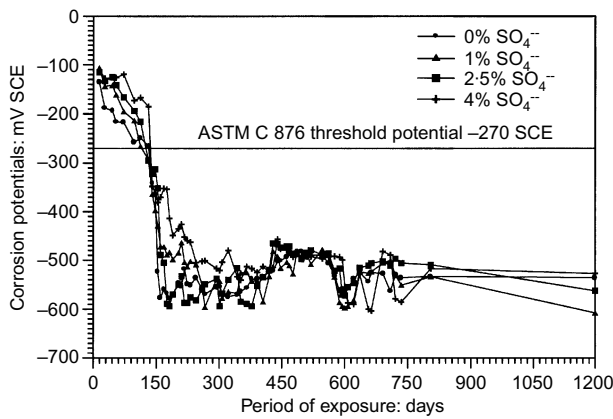


Fig. 8. Corrosion potentials on steel bars in the PC concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

corrosion potentials in these specimens were also initially high but decreased with the period of exposure. However, these values were almost stable after 200 days of exposure.

Corrosion current density

The I_{corr} on steel in the BFS cement concrete specimens exposed to 5% NaCl solutions admixed with 0, 1, 2.5 and 4% SO_4^{2-} , derived from sodium sulphate, is plotted against the period of exposure in Fig. 9. These values were very low and similar in all the specimens in the initial stages of exposure of up to 125 days. After this period, the I_{corr} started to deviate and increase with the time of exposure. The I_{corr} on steel in the concrete specimens exposed to sodium chloride plus sodium sulphate was more than that in the specimens exposed to sodium chloride only. Further, the I_{corr} increased with increasing sodium sulphate concentration.

Figure 10 depicts the I_{corr} on steel in the BFS cement concrete specimens exposed to 5% NaCl solutions

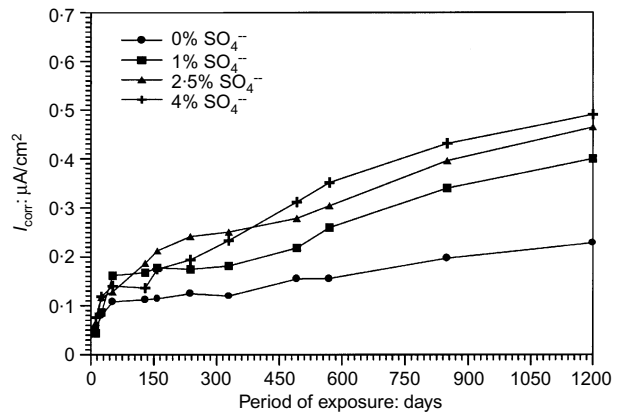


Fig. 9. Corrosion current density on steel in the BFS cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

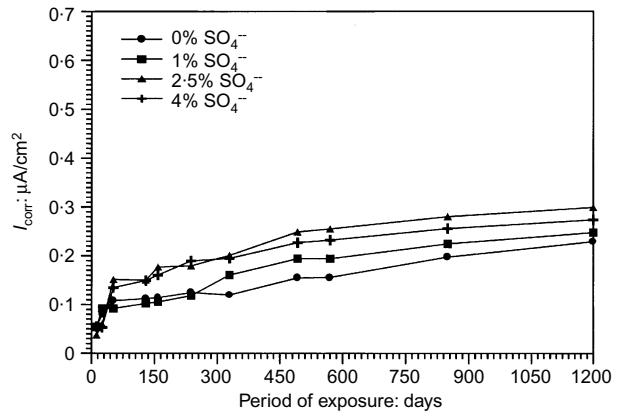


Fig. 10. Corrosion current density on steel in the BFS cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

admixed with magnesium sulphate. The I_{corr} increased with the period of exposure. Initially, the I_{corr} was very low and similar in all the specimens. However, after 150 days of exposure, the I_{corr} started to increase. The I_{corr} in the concrete specimens exposed to sodium chloride plus magnesium sulphate was more than that in the specimens exposed to sodium chloride only. Further, the I_{corr} increased with increasing concentration of magnesium sulphate up to 2.5% SO_4^{2-} , beyond which the I_{corr} decreased slightly.

The I_{corr} values on steel in the SF and FA cement concrete specimens exposed to 5% NaCl solutions admixed with sodium sulphate are shown in Figs 11 and 12, respectively. The trend of these data was similar to that exhibited by BFS cement concrete specimens exposed to similar solutions.

Figures 13 and 14 show the I_{corr} on steel in the SF and FA cement concrete specimens exposed to 5% NaCl solution admixed with magnesium sulphate, respectively. The trend of these data was similar to that

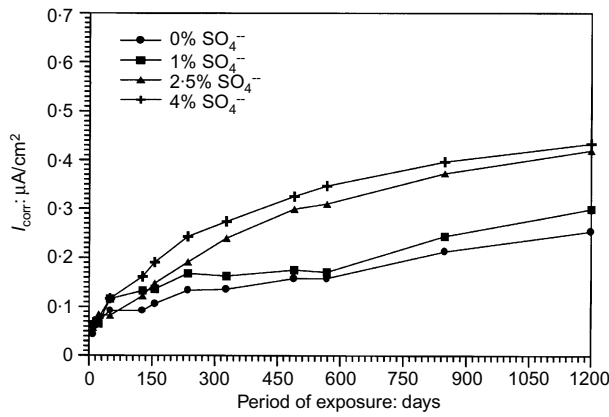


Fig. 11. Corrosion current density on steel in the SF cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

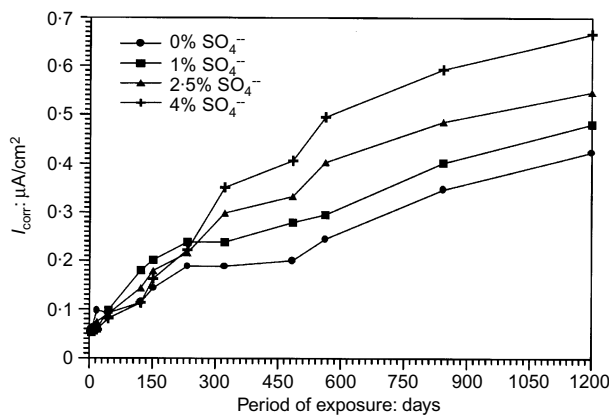


Fig. 12. Corrosion current density on steel in the FA cement concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

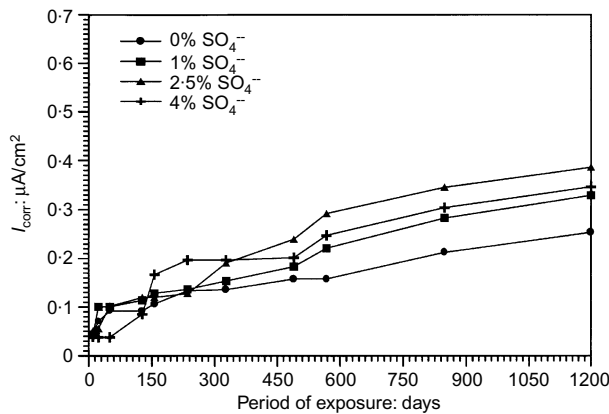


Fig. 13. Corrosion current density on steel in the SF cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

exhibited by the BFS cement concrete specimens exposed to similar solutions.

The variation of I_{corr} on steel in the PC concrete specimens exposed to 5% NaCl solutions admixed with

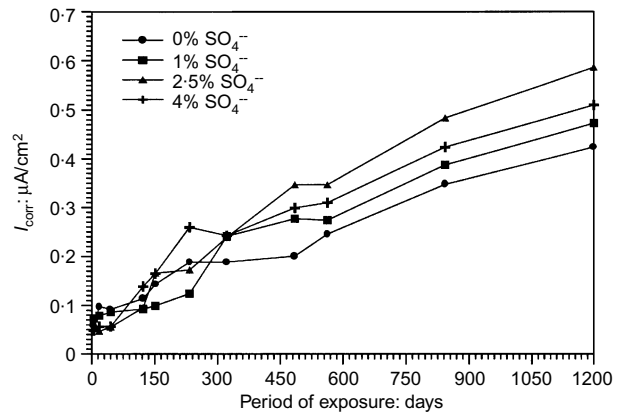


Fig. 14. Corrosion current density on steel in the FA cement concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

0, 1, 2.5 and 4% SO_4^{2-} , derived from sodium sulphate, is plotted against the period of exposure in Fig. 15. The I_{corr} increased almost linearly with the period of exposure. These values were very low and similar in all the concrete specimens in the initial stages of exposure of up to 90 days. However, after this time, the I_{corr} started to increase and deviate and it was significantly high in the specimens exposed to sodium chloride plus sodium sulphate compared to that in the specimens exposed to only sodium chloride.

Figure 16 shows the variation of I_{corr} with time in the PC concrete specimens exposed to 5% NaCl solutions admixed with 0, 1, 2.5 and 4% SO_4^{2-} , derived from magnesium sulphate. Almost a linear increase in the I_{corr} values, with the period of exposure, was observed in all the specimens. Initially, these values were low and approximately similar in all the specimens. However, they increased with time, and after 160 days of exposure, the I_{corr} started to increase and deviate. The I_{corr} on steel in the concrete specimens exposed to

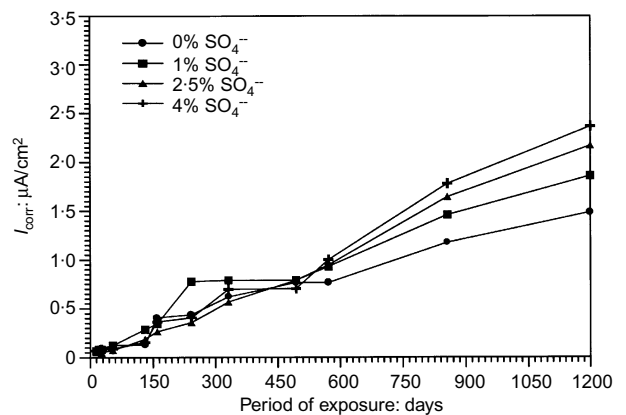


Fig. 15. Corrosion current density on steel bars in the PC concrete specimens exposed to 5% NaCl solution admixed with varying sodium sulphate concentration

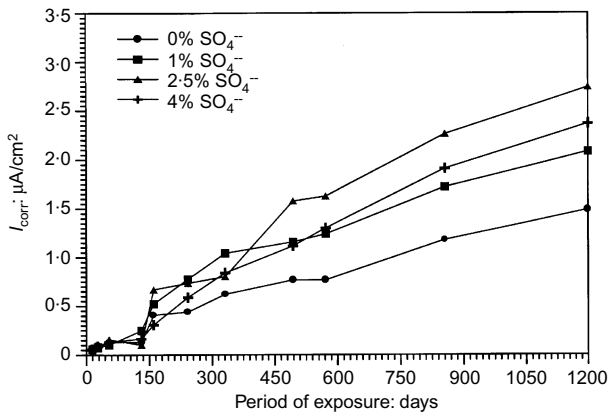


Fig. 16. Corrosion current density on steel bars in the PC concrete specimens exposed to 5% NaCl solution admixed with varying magnesium sulphate concentration

sodium chloride plus magnesium sulphate solution was more than that in the concrete specimens exposed to sodium chloride solutions only. Further, the I_{corr} values increased with increasing magnesium sulphate concentration of up to 2.5%, beyond which, the I_{corr} decreased slightly. The decrease in the I_{corr} due to excess of magnesium sulphate (4% SO_4^{2-}) may be attributed to the formation of magnesium hydroxide. This leads to a blockage of the pores in the concrete specimens exposed to these solutions, decreasing the diffusion of oxygen and hence retarding the ingress of aggressive species to the steel surface.

The I_{corr} on steel in PC and blended cement concrete specimens exposed to sodium chloride plus sodium sulphate solutions is plotted against sulphate concentration in Fig. 17. The I_{corr} increased almost linearly with increasing concentration of sodium sulphate. Further, the I_{corr} values in the PC concrete specimens were higher than those in the blended cement concretes. The I_{corr} on steel in the PC and blended cement concrete specimens exposed to sodium chloride plus magnesium

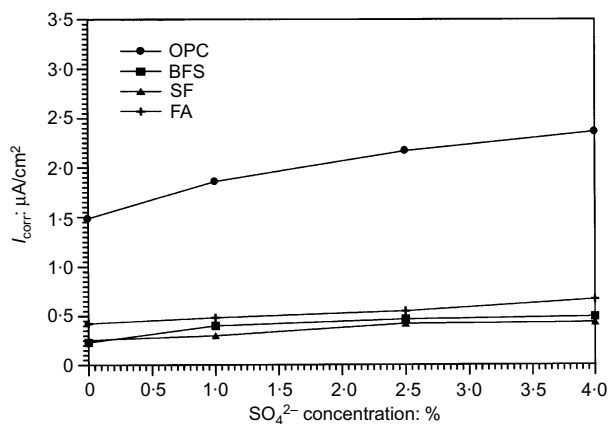


Fig. 17. Variation of I_{corr} with sulphate concentration in the plain and blended cement concrete specimens exposed to 5% NaCl plus sodium sulphate solutions

sulphate is plotted against sulphate concentration in Fig. 18. In these specimens also, the I_{corr} increased with increasing concentration of magnesium sulphate up to 2.5% SO_4^{2-} . However, it decreased slightly when the magnesium sulphate concentration increased from 2.5 to 4% SO_4^{2-} . The I_{corr} values in the PC concrete specimens were more than those in the blended cement concretes.

Discussion

The corrosion potentials–time curves, discussed in Figs 1–8, were utilised to evaluate the time to initiation of reinforcement corrosion, based on the ASTM C876 criterion of -270 mV SCE. These values are summarised in Table 3. The time to initiation of reinforcement corrosion did not vary significantly with the sulphate concentration and the cation type. However, the time to initiation of reinforcement corrosion was influenced by the type of cement. For example, reinforcement corrosion in PC concrete specimens started earlier than in the blended cement concrete specimens.

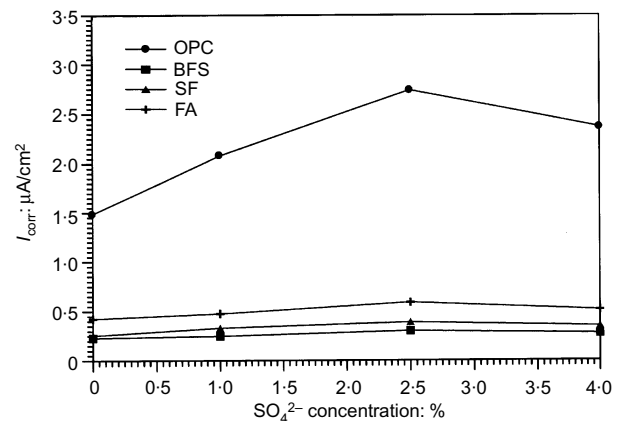


Fig. 18. Variation of I_{corr} with sulphate concentration in the plain and blended cement concrete specimens exposed to 5% NaCl plus magnesium sulphate solutions

Table 3. Time to initiation of reinforcement corrosion in the plain and blended cement concrete specimens exposed to sodium chloride plus sodium sulphate or magnesium sulphate solutions

Exposure solution	Time to initiation of reinforcement corrosion: days		
	PC	SF	FA
5% NaCl	132	201	159
5% NaCl + 1% SO_4^{2-} (Na_2SO_4)	117	205	155
5% NaCl + 2.5% SO_4^{2-} (Na_2SO_4)	146	158	153
5% NaCl + 4% SO_4^{2-} (Na_2SO_4)	133	158	168
5% NaCl + 1% SO_4^{2-} ($MgSO_4$)	115	134	160
5% NaCl + 2.5% SO_4^{2-} ($MgSO_4$)	126	152	151
5% NaCl + 4% SO_4^{2-} ($MgSO_4$)	137	88	157

The longer time to initiation of reinforcement corrosion noted in the blended cement concretes may be attributed to their dense structure, which retards the diffusion of chloride ions to the steel surface. Among blended cements, corrosion initiation in the FA cement concrete specimens was noted earlier than that in the SF cement concrete specimens. The delay in the initiation of reinforcement corrosion in the SF cement concrete may be attributed to its dense structure compared to FA cement concrete.

The time to initiation of reinforcement corrosion in the BFS cement concrete specimens was not evaluated using the ASTM C 876 criterion as the corrosion potentials in most of the specimens were more negative than -270 mV SCE from the initial stages of exposure. Several researchers^{12–14} have reported similar results. Macphee¹⁵ attributed the low corrosion potentials on steel in the BFS cement concrete specimens to the reducing effect of sulphur species, namely S^{2-} , S_2O_3 , etc., derived from the slag. The sulphur species present in the BFS cement create a reducing environment resulting in low corrosion potentials on steel in these specimens.

The data on time to initiation of reinforcement corrosion, summarised in Table 3, also indicate that the presence of sulphate ions, in conjunction with chloride ions, does not significantly affect the kinetics of corrosion initiation. For similar concretes, the time to initiation of reinforcement corrosion in the specimens exposed to the chloride solution was almost similar to that in the specimens exposed to chloride plus sulphate solutions. Such a behaviour is understandable and could be ascribed to the diffusion of chloride and sulphate ions. When both chloride and sulphate ions are present in an exposure environment, the former ions diffuse through the concrete faster than the latter ions. The faster diffusion rates of chloride ions, compared to the sulphate ions, have been reported by several researchers.^{16–20}

Due to their faster diffusion, chloride ions reach the steel surface earlier than the sulphate ions. As such, the insignificant effect of the sulphate ions on the time to initiation of reinforcement corrosion is understandable. The data in Table 3, however, indicate that the type of cement significantly influences the time to initiation of reinforcement corrosion. Corrosion initiation occurred earlier in the PC concrete than in the blended cement concretes. This behavior may be attributed to the lower chloride diffusion found with the blended cements and their dense structure, compared to the plain cement.

The data in Figs 17 and 18 indicate that the I_{corr} on steel in the PC concrete specimens is much more than in the blended cement concrete specimens. Further, the I_{corr} on steel in the concrete specimens exposed to chloride plus sulphate solutions was more than that in the concrete specimens exposed to chloride solution only. The increase in the I_{corr} in the specimens exposed to chloride plus sulphate solution was 1.1 to 2.2 times that in the concrete specimens exposed to sodium

chloride solution only. This increase may be attributed to an increase in the concentration of free chloride ions in the pore solution and to a decrease in the electrical resistivity of concrete due to the presence of both sulphate and chloride ions

The effect of sulphate ions on the chloride binding of cements has been reported earlier.^{5,21–23} In the presence of both sulphate and chloride ions, the proportion of chlorides bound by cement is less than that when only chloride ions are present. The presence of excess of free chloride ions around the steel surface accelerates the rate of corrosion by mainly decreasing the electrical resistivity of concrete. Saleem *et al.*²⁴ reported a decrease in the electrical resistivity of concrete from 40 to 8 k Ω .cm when the sulphate contamination was increased from 7.2 to 43.2 kg/m³. Further, their results indicated that in the presence of sulphate ions, the tolerable level of chloride concentration, for reinforcement corrosion, decreased from 19.28 to 4.8 kg/m³.

The I_{corr} is also influenced by the concentration of the sulphate ions. It increased with increasing concentration of both sodium and magnesium sulphate. This trend was particularly noted in PC concrete. However, the change in the I_{corr} with sulphate concentration was not as significant in the blended cement concretes. A comparison of data in Figs 17 and 18 does not indicate a significant variation in the I_{corr} values in the concrete specimens exposed to sodium sulphate or magnesium sulphate. This indicates that the cation type associated with the sulphate ions did not significantly affect the rate of reinforcement corrosion, within the period of this study. However, surface deterioration was noted in the concrete specimens exposed to sodium chloride plus magnesium sulphate, when the SO_4^{2-} concentration was more than 1% in SF and BFS cement concretes and more than 2.5% in PC and FA cement concretes.²⁵ Therefore, an increase in the corrosion activity may be expected due to deterioration of concrete when exposed to high concentrations of magnesium sulphate.

The I_{corr} was also affected significantly by the type of cement. The I_{corr} on steel in the blended cement concretes was less than that in the plain cement concrete. The I_{corr} in the blended cement concretes was about 10–30% of that in the plain cement concrete. This may be attributed to the high electrical resistivity and dense structure of the blended cement concretes compared to plain cement concrete. The lower I_{corr} values noted in the blended cement concretes, compared to plain cement concrete, indicate that the former cements are preferable to the latter in the chloride plus sulphate environments.

Conclusion

No significant variation in the time to initiation of reinforcement corrosion was noted in the concrete specimens exposed to chloride or chloride plus sulphate

solution, indicating that the sulphate ions do not significantly influence the initiation of chloride-induced reinforcement corrosion.

The time to initiation of reinforcement corrosion was influenced by the type of cement rather than the sulphate concentration and the cation type associated with the sulphate ions. The corrosion initiation occurred earlier in the Portland cement concrete than in the blended cement concretes.

The I_{corr} on steel in the plain and blended cement concrete specimens, exposed to sodium chloride plus sodium sulphate or magnesium sulphate, was more than that in the concrete specimens exposed to sodium chloride solution only. The I_{corr} on steel in the plain and blended cement concrete specimens exposed to sodium chloride plus sodium sulphate or magnesium sulphate solutions increased with increasing sulphate concentration. This increase was 1.1 to 2.2 times that in the concrete specimens exposed to only sodium chloride solution. However, in the case of concrete specimens exposed to magnesium sulphate, the I_{corr} increased with increasing magnesium sulphate concentration of up to 2.5% SO_4^{2-} , beyond this concentration, the I_{corr} decreased slightly. The increase in the I_{corr} on steel in the concrete specimens exposed to sodium chloride plus sodium sulphate or sodium chloride plus magnesium sulphate solutions may be attributed to a decrease in the chloride binding and electrical resistivity of concrete due to the presence of chloride and sulphate ions.

The I_{corr} on steel in the blended cement concrete specimens was much less than that in the plain cement concrete specimens. The I_{corr} in the blended cement concrete specimens was about 10–30% of that in the plain cement concrete specimens. Though deterioration of concrete was noted on the concrete specimens exposed to chloride plus magnesium sulphate, the initiation and rate of reinforcement corrosion was not significantly different from those exposed to chloride plus sodium sulphate.

The lower I_{corr} values found in the blended cement concretes compared to plain cement concrete, indicate that the former cements are preferable in the chloride plus sulphate environments.

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Discussion contributions on this paper should reach the editor by 1 April 2003