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Long term Effect of Sulfate Ions and Associated Cation Type on Chloride-Induced Reinforcement Corrosion in Portland Cement Concretes

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Abstract

This paper reports the influence of sulfate concentration on chloride-induced reinforcement corrosion in Portland cement concretes (with C_3A varying from 3.6 to 9.65%). The concrete specimens were exposed to mixed chloride and sulfate solutions for a period of 1200 days. The chloride was fixed at 5% NaCl for all solutions, while the sulfate concentration was varied to represent that typical of sulfate-bearing soil and ground water. The study included an assessment of the effect of cation type associated with sulfate ions, namely Na^+ and Mg^{++} , on chloride-induced reinforcement corrosion, an important factor that has received little attention. Reinforcement corrosion was evaluated by measuring corrosion potentials and corrosion current density at regular intervals. The results indicate that the presence of sulfate ions in the chloride solution did not influence the time to initiation of chloride-induced reinforcement corrosion, but the rate of corrosion increased with increasing sulfate concentration. Further, the rate of chloride-induced reinforcement corrosion in the concrete specimens exposed to sodium chloride plus magnesium sulfate solutions was more than that in the specimens exposed to sodium chloride plus sodium sulfate solutions.

Keywords: Chloride-induced reinforcement corrosion, Sulfate cation, Sulfate concentration.

1. Introduction

The low durability of reinforced concrete structures is of major concern to the construction industry throughout the world. The deterioration of concrete structures in temperate climatic conditions, as in Europe and North America, is mainly attributed to reinforcement corrosion that is caused by ingress of deicer salts or carbonation. Insufficient concrete cover over reinforcing steel and/or poor quality concrete accelerates the deterioration processes. Accelerated deterioration of reinforced concrete structures is also noted in the Arabian Gulf. The environmental and geomorphical conditions in the coastal areas of the Arabian Gulf contribute to a reduction in the useful service-life of concrete structures in this region, particularly the contamination of soil and ground water with chloride and sulfate salts. The daily and seasonal variations in the temperature and the humidity accelerate the rate of deterioration. The ambient temperature in the Arabian Gulf is high (40 to 45 °C) compared to that noted in the USA or Europe (15 to 25 °C). The direct solar radiation effect raises the temperature at the concrete surface to as high as 70 to 80 °C. This thermal effect influences the over all mechanisms of concrete deterioration processes, such as reinforcement corrosion, sulfate attack, salt weathering, and shrinkage and thermal cracking. Further, the rate of reinforcement corrosion increases rapidly with increasing ambient temperature.

Chloride ions are considered to be the primary cause of reinforcement corrosion (outweighing that due to carbonation) and the rate of corrosion is strongly influenced by environmental factors and concrete properties, such as permeability, type of cement, intensity of cracks, and concrete cover. Chlorides are contributed to

the concrete by the admixtures, aggregates and/or mixing and curing water. Alternatively, they may penetrate the hardened concrete from the external environment, such as seawater, soil and groundwater that contain sulfate and chloride salts.

The precise role of sulfate ions on the mechanisms of chloride-induced reinforcement corrosion is not known. The conjoint presence of chloride and sulfate ions may significantly affect reinforcement corrosion. Limited data developed by Al-Amoudi et al. [1-3] indicated that sulfate ions significantly influence the mechanism of chloride-induced reinforcement corrosion. In these studies [1-3] only two concentrations of sulfate ions (0.55 and 2.1%) were investigated. The required concentrations of sulfate ions were obtained by mixing equivalent quantities of sodium sulfate and magnesium sulfate salts. Due to this mixing, the effect of cation type associated with the sulfate ions on reinforcement corrosion could not be evaluated.

This study was conducted to assess the effect of sulfate concentration and the associated cation type on chloride-induced reinforcement corrosion in concretes prepared with Portland cements (ordinary and sulfate resisting).

2 Experimental Program

2.1 *Materials and Specimen Preparation*

Reinforced concrete specimens were prepared using two ordinary Portland cements (OPC-A; C₃A: 8.5% and OPC-B; C₃A: 9.65%), and one sulfate-resisting Portland cement (SRPC; C₃A: 3.6%). The chemical composition of the cements is shown in Table 1.

The concrete mixtures were prepared with an effective water-cement ratio of 0.45 and total cement content of 350 kg/m³. Crushed dolomitic limestone with a specific gravity of 2.43 and absorption of 3% was used as coarse aggregate and dune sand with a specific gravity of 2.53 and absorption of 0.57% was used as fine aggregate. The coarse and fine aggregates were washed to remove 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.

Reinforced concrete specimens, 75 mm in diameter and 150 mm high, with a single 12 mm diameter steel bar centered in the middle were prepared. An effective cover of 25 mm was provided at the bottom of the specimen. The steel bars were cleaned and coated with cement paste followed by an epoxy coating at the concrete-air interface and at the bottom of the bar to avoid crevice corrosion at these locations. The steel bars were cleaned mechanically with a silicon carbide paper, wherever necessary, and degreased with acetone prior to casting in concrete.

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 in the laboratory temperature for 24 hours. They were then demolded and cured in potable water maintained at 25 °C for 28 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 test solutions.

2.2 Exposure Solutions

The concrete specimens were exposed to varying sulfate concentrations as detailed in Table 2. All the exposure solutions contained 5% NaCl and varying

concentrations of sodium or magnesium sulfate. The 5% NaCl solution used in this study represents the chloride concentration in the seawater. The sulfate concentration was varied from 0 to 4% to systematically evaluate the effect of these ions on chloride-induced reinforcement corrosion. Further, the 4% SO_4^- is representative of the sulfate concentration in sabkha soils. Three reinforced concrete specimens from each concrete mix were placed in the selected exposure solution. Reinforced concrete specimens were partially immersed in the test solution. The level of the solution was adjusted, so that only 85 to 90 mm of the bottom of the specimens was in the solution. The chloride and sulfate concentration in the solutions was monitored and adjusted every two weeks.

2.3 Monitoring of Reinforcement Corrosion

Reinforcement corrosion was evaluated by measuring corrosion potentials and corrosion current density (I_{corr}). The corrosion potentials provide information on the time to initiation of reinforcement corrosion under laboratory conditions, while the corrosion current density provides information on the rate of reinforcement corrosion. These two components together constitute the service life model suggested by Tutti [4]. The corrosion potentials were measured using a saturated calomel reference electrode (SCE) and a high impedance voltmeter.

The corrosion current density was measured using the linear polarization resistance method (LPRM). Steel was polarized to ± 20 mV of the corrosion potential at a scan rate of 0.1 mV/s utilizing a Potentiostat/Galvanostat. Corrosion current density was then calculated using the Stern-Geary formula [5]:

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

Where: I_{corr} = corrosion current density, $\mu\text{A}/\text{cm}^2$

R_p = polarization resistance, $\text{K}\Omega.\text{cm}^2$

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

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

The Tafel constants are normally obtained by polarizing 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 active condition and 52 mV for steel in passive condition is used to calculate the corrosion current density [6]. In another study, Dehwah et al. [7] conducted potentiodynamic studies on concrete specimens and the results indicated that the Tafel constants are approximately 120 mV/decade. Lambert et al. [8] reported a good correlation between corrosion rate determined using these values and the gravimetric weight loss method. In view of the aforesaid findings, Tafel constants of 120 mV were adopted for the calculation of corrosion current density.

3 Results

3.1 Effect of Chloride-Sulfate Exposure on Corrosion Initiation

The corrosion potentials on steel in the SRPC concrete specimens exposed to 5% NaCl solution, admixed with 0, 1, 2.5 and 4% SO_4^{2-} , derived from sodium sulfate, are depicted in Figure 1. Initially, the corrosion potentials were high (less negative) and decreased with the period of exposure. However, after 180 days of exposure, the corrosion potentials stabilized in all the specimens. Figure 2 shows the corrosion

potentials in the SRPC concrete specimens exposed to sodium chloride solution admixed with magnesium sulfate. In these specimens also the corrosion potentials were high in the initial period of exposure but then decreased almost linearly with the period of exposure.

The corrosion potentials on steel in the OPC-A (C_3A : 8.5%) concrete specimens exposed to sodium chloride solution admixed with sodium or magnesium sulfate, are plotted in Figures 3 and 4, respectively. The trends of these data are similar to that of the SRPC specimens except that the long-term trend is more stable with the magnesium sulfate. Figures 5 and 6 depict the corrosion potentials on steel bars in the OPC-B (C_3A : 9.65%) concrete specimens exposed to sodium chloride solution admixed with sodium or magnesium sulfate, respectively. In these specimens also the corrosion potentials decreased with time and were stable after about 150 days and the trend of these data is similar to that noted in the OPC-A concrete specimens exposed to similar solutions.

The time-corrosion potential curves, discussed in Figures 1 through 6, were used to evaluate the time to initiation of reinforcement corrosion, based on the ASTM C876 criterion of -270 mV SCE. These values are summarized in Table 3. The time-to-initiation of reinforcement corrosion did not vary significantly with the cation type and the sulfate concentration. However, the time-to-initiation of reinforcement corrosion was influenced by the type of cement, namely the C_3A content. Reinforcement corrosion in SRPC concrete specimens (C_3A : 3.6%) occurred earlier than in the ordinary Portland cement concrete specimens. The delay in corrosion initiation with increasing C_3A content may be attributed to the complexation of

chloride ions with the C₃A. The similarity of the results for the two Portland cements demonstrates the repeatability of the trends observed.

3.2 *Effect of Chloride-Sulfate Exposure on Corrosion Current Density*

The corrosion current density (I_{corr}) on the steel bars in the SRPC concrete specimens exposed to 5% NaCl solutions admixed with 0, 1, 2.5 and 4% SO_4^- , derived from sodium sulfate, is depicted in Figure 7. The I_{corr} increased almost linearly with the period of exposure. These values were very low and similar in all the specimens in the initial stages of exposure of up to 90 days. However, after this time, the I_{corr} on steel in the concrete specimens exposed to sodium chloride plus sodium sulfate solutions was more than that in the specimens exposed to sodium chloride solution.

Figure 8 shows the variation of I_{corr} with time in the SRPC concrete specimens exposed to NaCl solution admixed with magnesium sulfate. Almost a linear increase in the I_{corr} values, with the period of exposure, was observed in all the specimens. Initially, the values were low and approximately the same in all the specimens. However, they increased with time and after 160 days of exposure, the I_{corr} on steel in the concrete specimens exposed to sodium chloride plus magnesium sulfate solution was significantly greater than that in the specimens exposed to only sodium chloride solution. Further, the I_{corr} values increased with increasing magnesium sulfate concentration of up to 2.5%. However, a slight decrease in the I_{corr} values were noted in the concrete specimens exposed to 4% SO_4^- . The latter may be attributed to the formation of magnesium hydroxide (brucite) which blocks the pores in the concrete specimens exposed to these solutions and decreases the diffusion of oxygen to the steel surface.

Figures 9 and 10 depict the I_{corr} on steel in the OPC-A (C_3A : 8.5%) and OPC-B (C_3A : 9.65%) concrete specimens exposed to sodium chloride plus sodium sulfate. The trend of these data was similar to that noted in the SRPC concrete specimens exposed to similar solutions.

Figures 11 and 12 depict the I_{corr} on steel in the OPC-A and OPC-B concrete specimens exposed to sodium sulfate solution, admixed with magnesium sulfate. The trend of these data was also similar to that noted in the SRPC concrete specimens exposed to similar solutions.

The I_{corr} on steel bars in the concrete specimens exposed to sodium chloride plus sodium or magnesium sulfate solutions are plotted against sulfate concentration in Figures 13 and 14. The I_{corr} increased almost linearly with increasing concentration of sodium sulfate, with magnesium it increased up to 2.5% SO_4^{2-} , but then decreased slightly when the SO_4^{2-} increased from 2.5 to 4%.

The I_{corr} on steel in the concrete specimens exposed to sodium chloride plus sodium or magnesium sulfate is plotted against C_3A in Figures 15 and 16. The I_{corr} values decreased with increasing C_3A content in cement with both types of cation, although the magnesium sulfate produced higher I_{corr} values.

4 Discussion

Corrosion of reinforcing steel is mainly attributed to chloride ions. It would be expected that the presence of sulfate ions would affect the mineralogical composition of hardened concrete and hence its corrosion-resisting characteristics. However, the precise role of sulfate ions in chloride-induced reinforcement corrosion is not very well investigated. The meager data available have indicated an increase in the

corrosion activity in the concrete specimens exposed to chloride plus sulfate environments compared to specimens exposed to only chloride environments. Treadaway et al. [9] investigated the effect of adding chloride and sulfate ions to concrete on reinforcement corrosion in the SRPC concrete specimens. The results of that study indicated higher reinforcement corrosion in the specimens admixed with sodium chloride plus sodium sulfate compared to those specimens admixed with only sodium chloride.

Al-Amoudi and Maslehuddin [1] indicated that while the sulfate ions are hardly able to induce reinforcement corrosion it was significant in the concrete specimens exposed to sodium chloride plus sodium sulfate solution. Reinforcement corrosion increased two times when the sulfate concentration in the 15.7% chloride solution was increased from 0.55 to 2.1%. An extension of this study [2] on plain and blended cements also indicated higher reinforcement corrosion in the specimens exposed to sodium chloride plus sodium sulfate than in the specimens exposed to only sodium chloride. Maslehuddin [10] indicated that the increase in reinforcement corrosion due to the addition of sulfate and chloride salts was 1.1 to 2.4 times that measured in the concrete specimens admixed with only sodium chloride.

As shown in Table 3, the data developed in the present study show that sulfate ions have little effect on the time to initiation of reinforcement corrosion. This may be attributed to the fact that corrosion initiation, when exposed to mixed chloride and sulfate environments, is predominantly governed by the relative diffusivity of these two ions. Several studies [11-15] have indicated that chloride ions diffuse much faster than sulfate ions into hardened cement paste. Oberholster [11] reported that the diffusion of chloride ions in concrete is generally 10 to 100 times faster than that of

sulfate ions. Rio and Turriziani [12] indicated that the diffusion of Cl^- in plain and blended cements was twice that of SO_4^{2-} . Stratfull [13] reported that concrete retained 14 times more chloride ions than sulfate ions. Barnes and Roy [14] reported that the diffusion rates of SO_4^{2-} is two to five times that of Na^+ . Bakker [15] indicated that the diffusion of chloride ions is considerably faster than SO_4^{2-} and other cations, whilst Oberholster [11] reported that the diffusion coefficient of chloride ions in hardened cement pastes increases when they are associated with divalent ions compared to monovalent ions.

In the present study, the corrosion current density on steel in the concrete specimens exposed to chloride-sulfate environments was more than that in the specimens exposed to only chloride environments. Further, the I_{corr} increased with increasing sulfate concentration.

The increase in the I_{corr} in the concrete specimens exposed to chloride plus sulfate solutions may be attributed to the following two factors:

1. an increase in the concentration of free chloride ions in the pore solution due to the concurrent presence of sulfate and chloride ions; and
2. a decrease in the electrical resistivity of concrete due to the conjoint presence of sulfate and chloride ions.

The combined presence of chloride and sulfate ions increases the concentration of free chloride ions in the pore solution. This increase in the free-chloride ion concentration is ascribed to the simultaneous reaction of C_3A with both chloride and sulfate ions. Chloride ions normally react with C_3A in cement to form an insoluble compound known as calcium chloro-aluminate hydrate ($\text{C}_3\text{A} \cdot \text{CaCl}_2 \cdot 10\text{H}_2\text{O}$), also

known as Friedel's salt. This chemical reaction reduces the quantity of free chloride ions in the pore solution thereby decreasing the chances of steel depassivation. When both chloride and sulfate ions are present, C_3A reacts concomitantly with both sulfate and chloride ions, as a result the proportion of chlorides bound is less than that when only chlorides are present.

The other factor that may contribute to an increase in the I_{corr} , due to the conjoint presence of chloride and sulfate ions is the reduction in the electrical resistivity of concrete. The electrical resistivity of concrete specimens admixed with chloride plus sulfate salts is generally lower than that of specimens admixed with only chloride ions. Khan [16] indicated that the electrical resistivity of concrete specimens admixed with sodium chloride was 1.4 to 7 times that of specimens admixed with sodium chloride plus sodium sulfate. Since the electrical resistivity of concrete is one of the factors controlling the rate of reinforcement corrosion, it is apparent that a reduction in the electrical resistivity will lead to increased rate of corrosion. According to Polder [17] a relationship between the resistivity of concrete and the corrosion rate of reinforcement should be due to the electrochemical nature of the corrosion process. In the corrosion cell circuit, ionic transport between the anode and cathode is one of the rate controlling factors. Similarly, in Bazant's model [18] the corrosion rate is inversely proportional to the resistivity.

The data developed in the present study suggest that the presence of both chloride and sulfate ions does not influence the time to initiation of reinforcement corrosion. This trend was noted in both ordinary and sulfate resisting Portland cement concrete specimens when exposed to either sodium or magnesium sulfate solution admixed with sodium chloride. Such a behavior has also reported by Al-Amoudi et al. [1-2].

However, in these studies [1-2] the sulfate ions were provided by both sodium and magnesium sulfate salts, while in the present study, the individual effect of Na_2SO_4 and MgSO_4 has been evaluated.

The data developed in the present study also indicate that the I_{corr} is influenced by the cation type associated with the sulfate ions, it being greater in the specimens exposed to MgSO_4 than to Na_2SO_4 . The I_{corr} increased with increasing concentration of sodium sulfate and magnesium sulfate. However, a marginal decrease in the I_{corr} was noted when the concentration of magnesium sulfate was increased from 2.5 to 4.0%, which may be attributed to the formation of $\text{Mg}(\text{OH})_2$ [19-20] that blocks the pores in the concrete specimens exposed to these solutions and retards the diffusion of oxygen to the steel surface.

5 Conclusions

The presence of sulfate ions in chloride environments did not affect the time-to-initiation of reinforcement corrosion. The time-to-initiation of reinforcement corrosion in the ordinary Portland cement concrete specimens was marginally more than that in the sulfate-resisting Portland cement concrete specimens.

The corrosion current density (I_{corr}) increased with increasing sodium sulfate concentration. The I_{corr} in the concrete specimens exposed to sodium chloride plus sodium sulfates was 1.1 to 2.0 times that in the concrete specimens exposed to only sodium chloride solution. Similarly, the I_{corr} increased with increasing magnesium sulfate concentration of up to 2.5% SO_4^{--} . This increase was 1.1 to 2.2 times that in the specimens exposed to only sodium chloride. The I_{corr} in the concrete specimens exposed to 4% SO_4^{--} (MgSO_4) was marginally less than that in the specimens exposed to 2.5% SO_4^{--} (MgSO_4).

The I_{corr} increased with increasing period of exposure and sulfate concentration and it was higher in the case of magnesium sulfate compared to sodium sulfate. The I_{corr} decreased with increasing C_3A content in cement. This behaviour may be attributed to increased chloride-binding by high C_3A cements which results in increased electrical resistivity in the ordinary Portland cements compared to sulfate resisting Portland cements.

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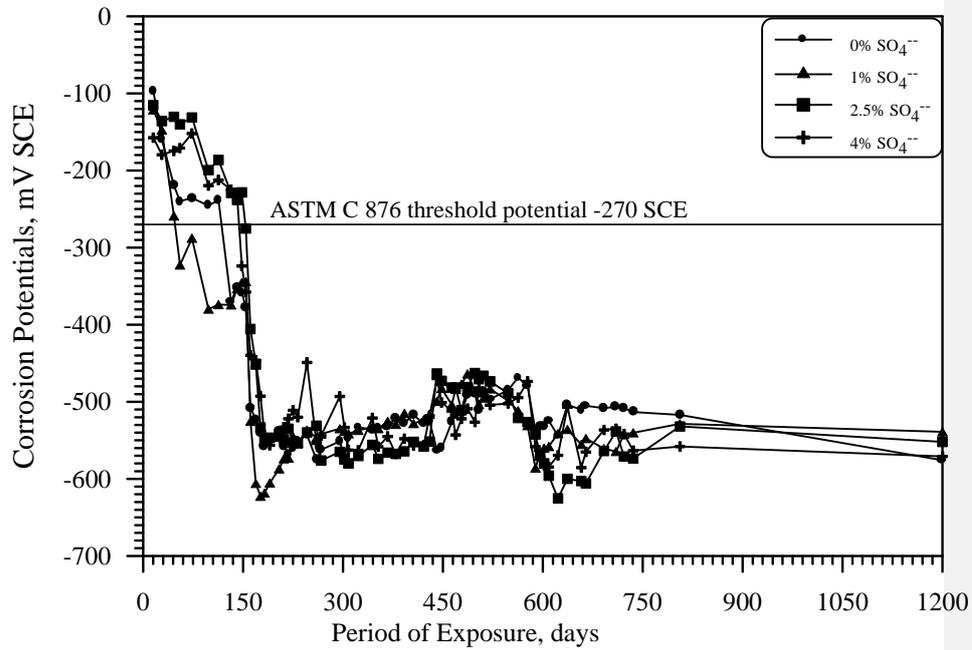


Figure 1: Corrosion potentials on steel bars in the SRPC concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

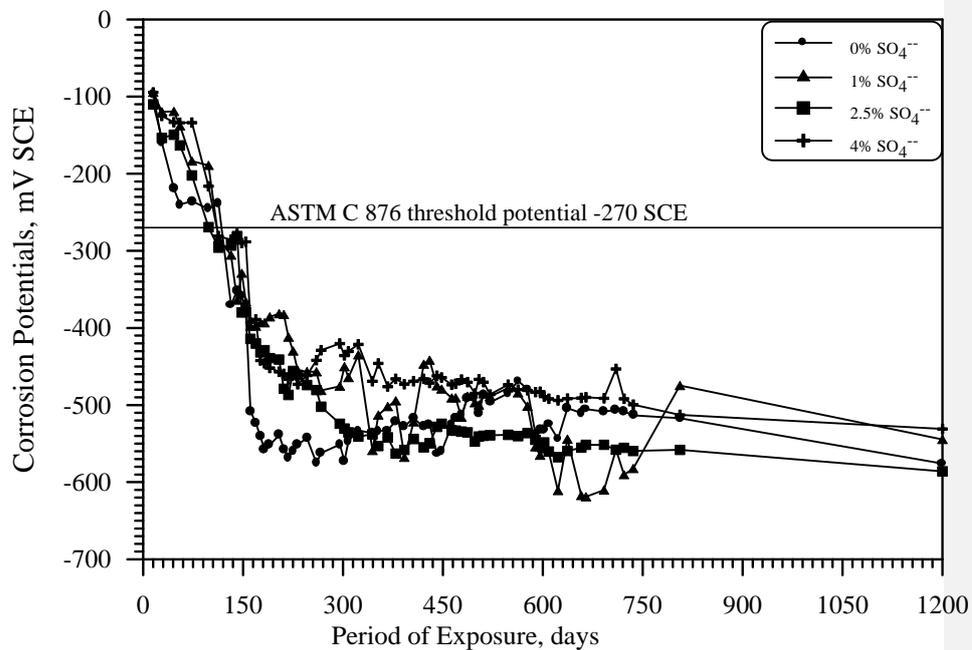


Figure 2: Corrosion potentials on steel bars in the SRPC concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

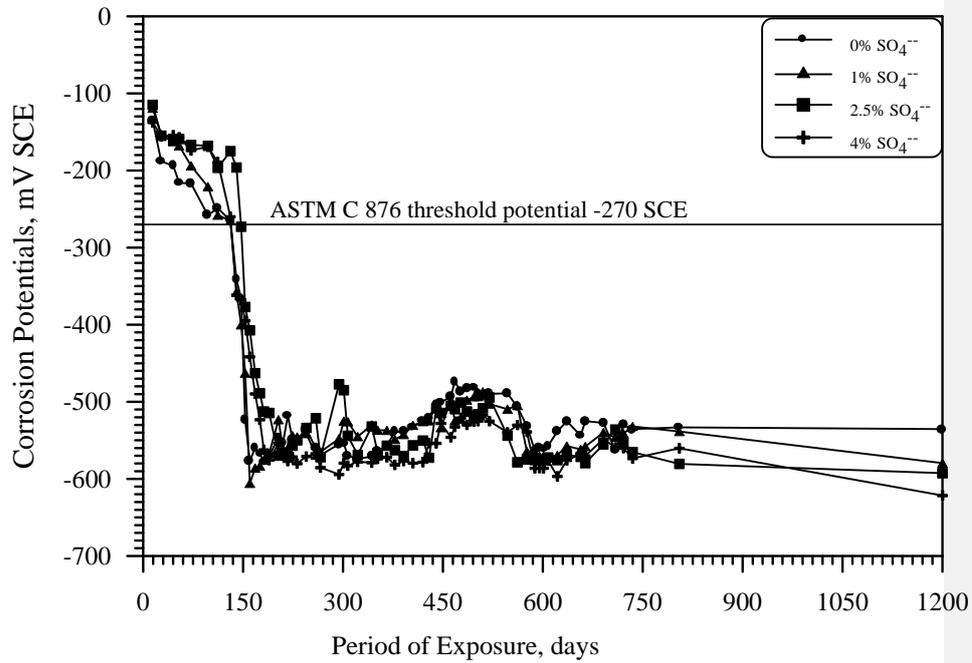


Figure 3: Corrosion potentials on steel bars in the OPC-A concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

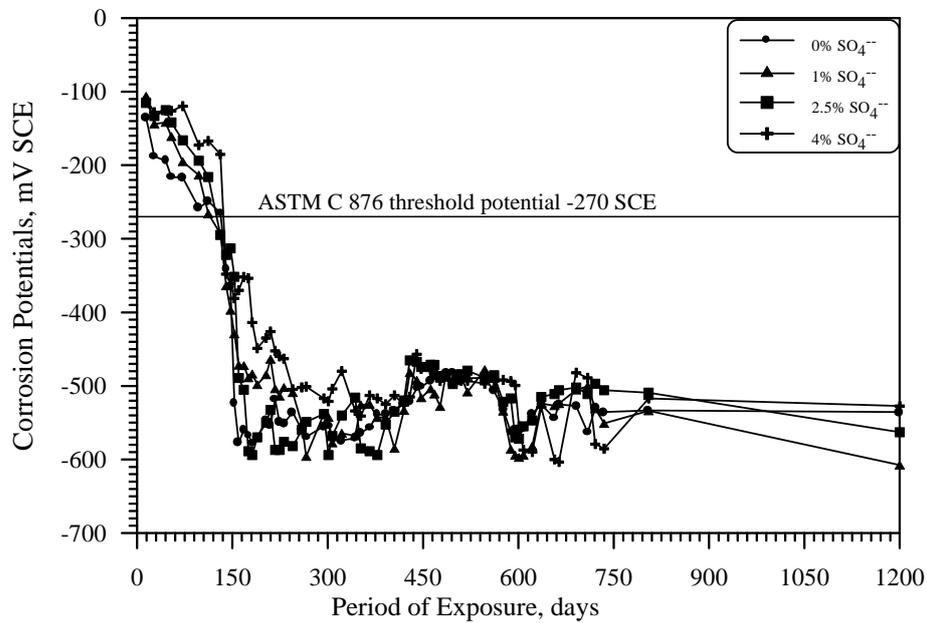


Figure 4: Corrosion potentials on steel bars in the OPC-A concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

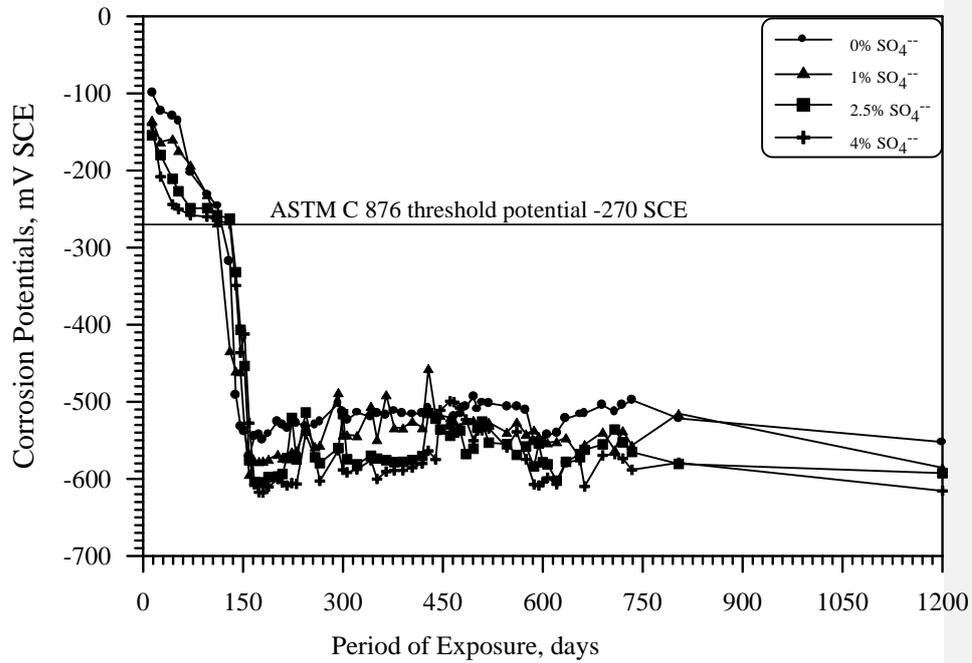


Figure 5: Corrosion potentials on steel bars in the OPC-B concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

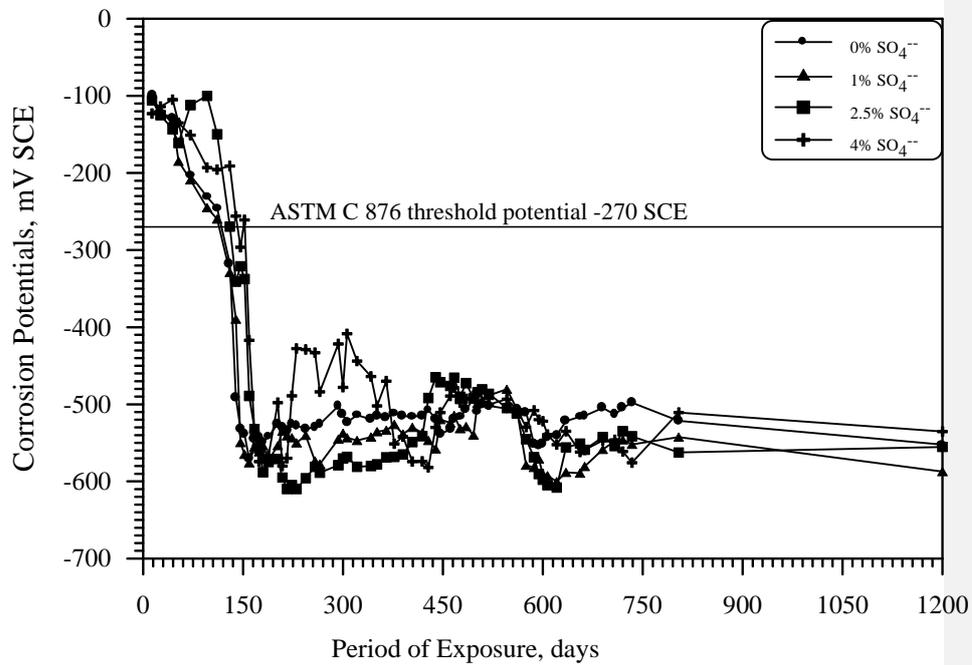


Figure 6: Corrosion potentials on steel bars in the OPC-B concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

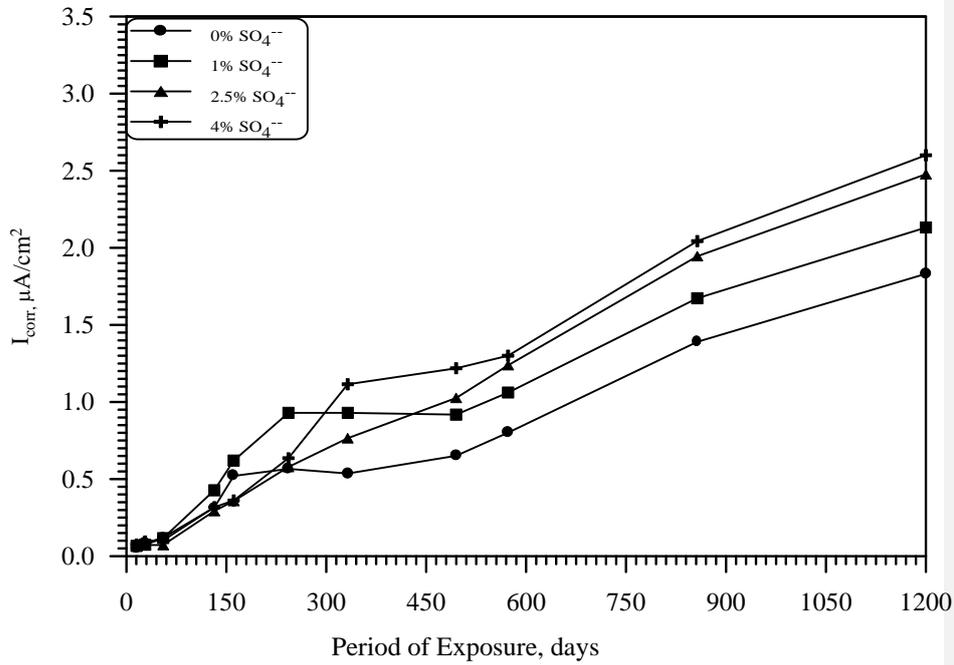


Figure 7: Corrosion current density on steel bars in the SRPC concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

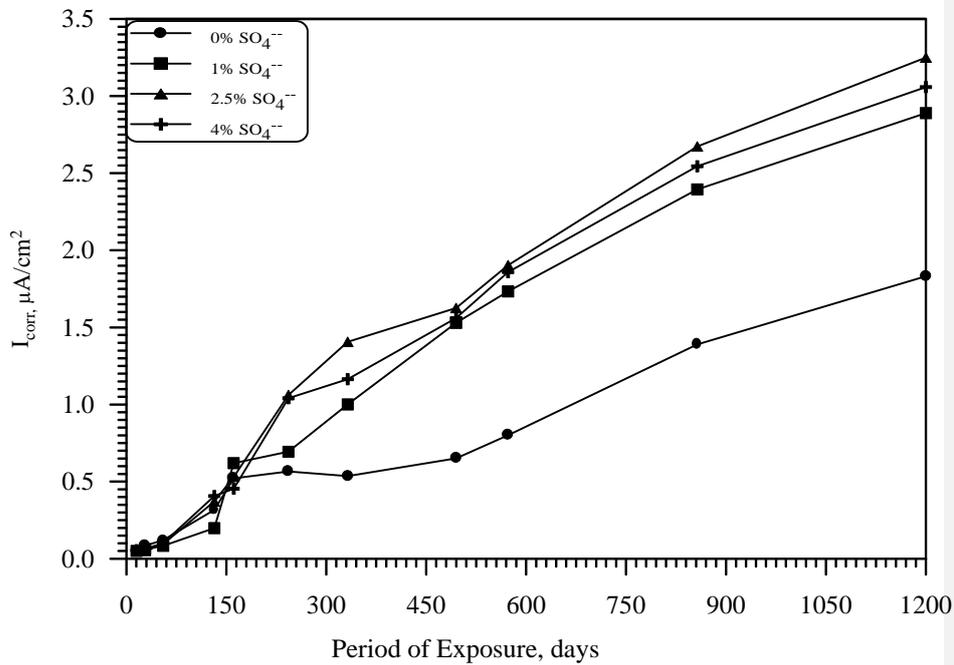


Figure 8: Corrosion current density on steel bars in the SRPC concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

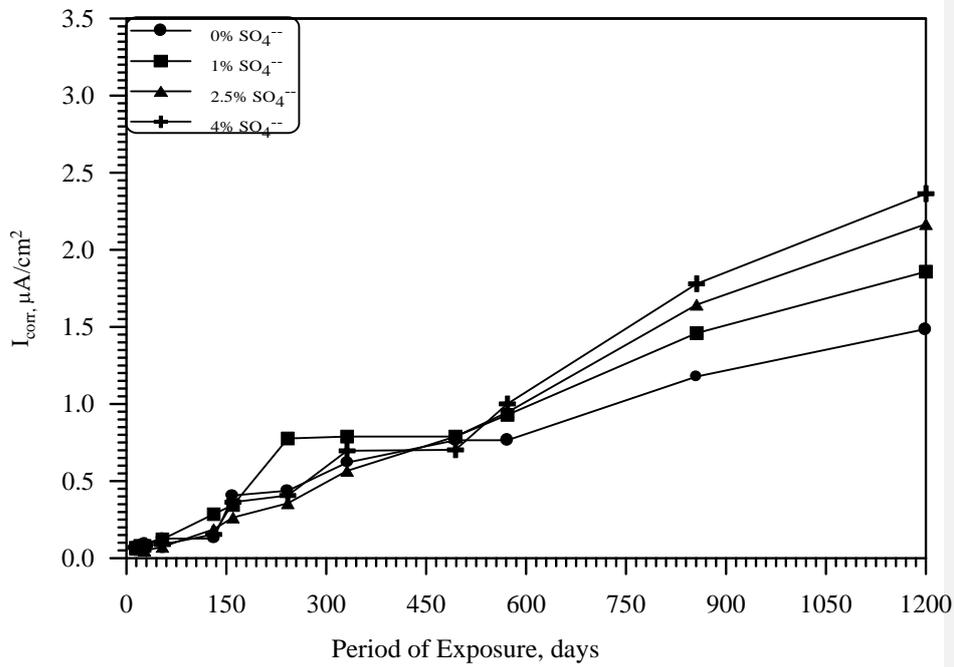


Figure 9: Corrosion current density on steel bars in the OPC-A concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

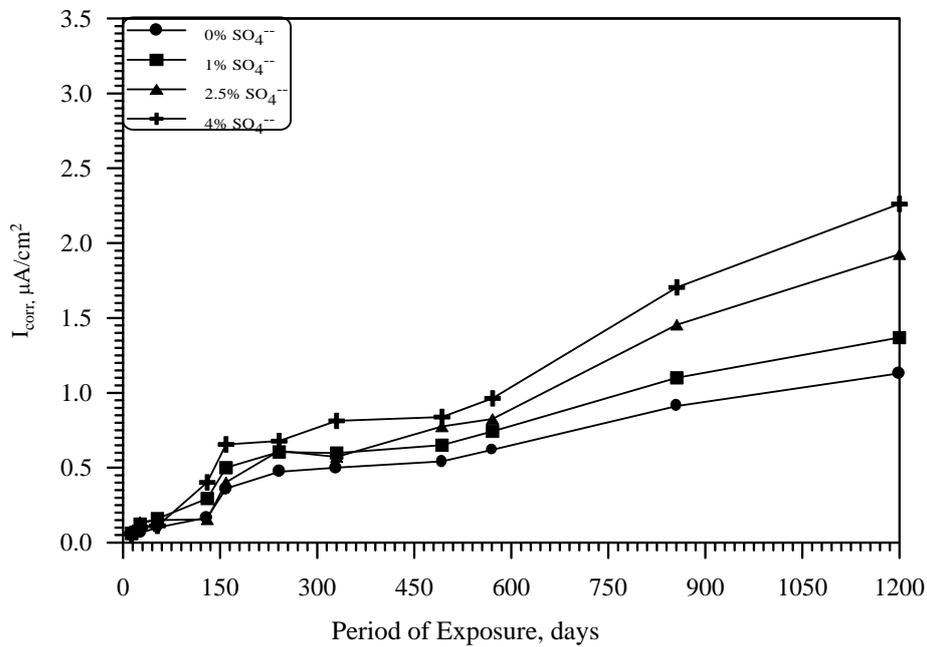


Figure 10: Corrosion current density on steel bars in the OPC-B concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

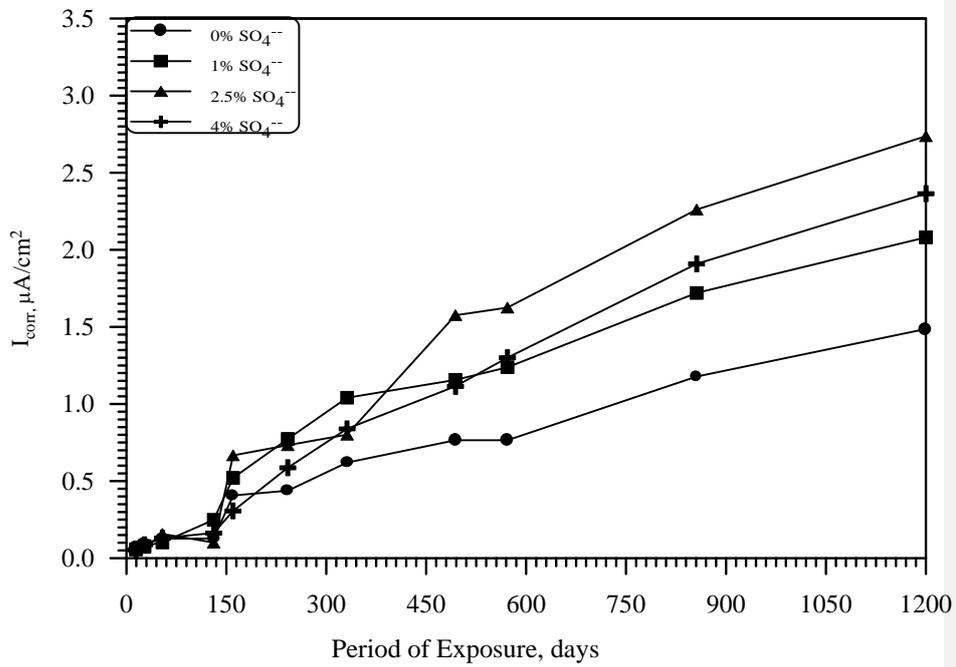


Figure 11: Corrosion current density on steel bars in the OPC-A concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

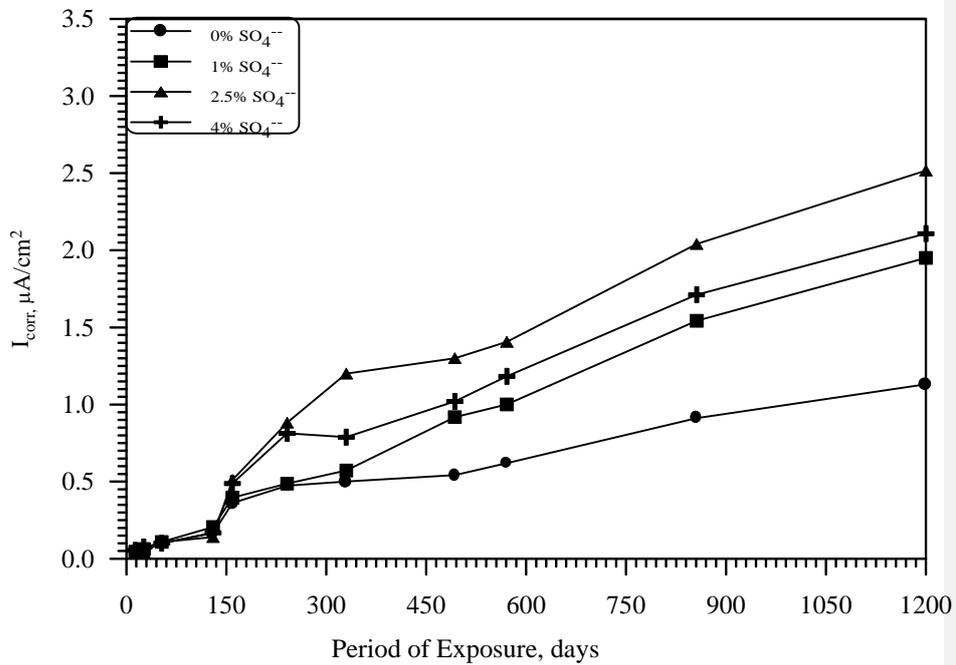


Figure 12: Corrosion current density on steel bars in the OPC-B concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

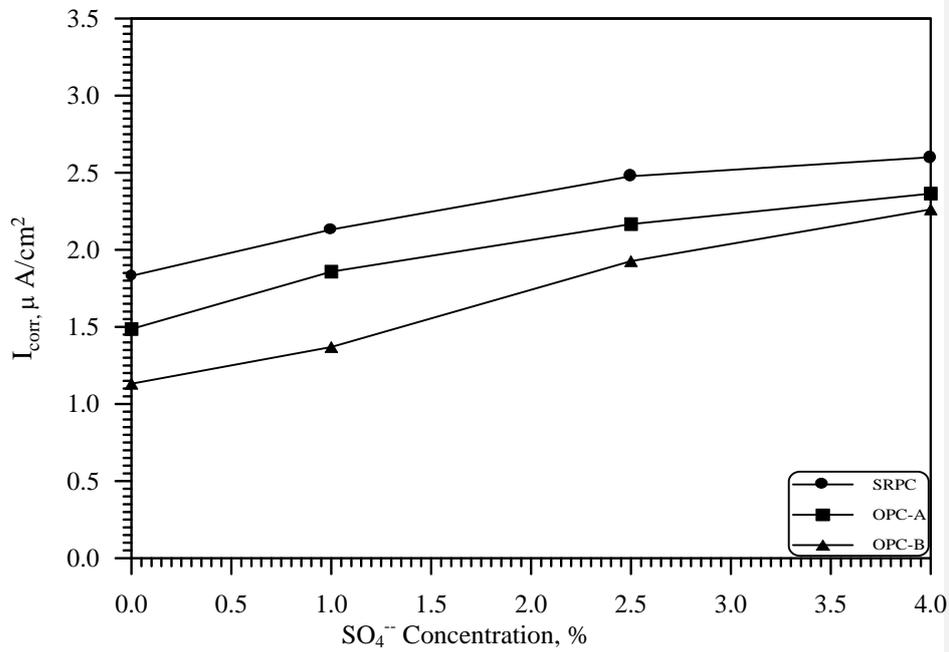


Figure 13: Variation of I_{corr} with sulfate concentration in the plain cement concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

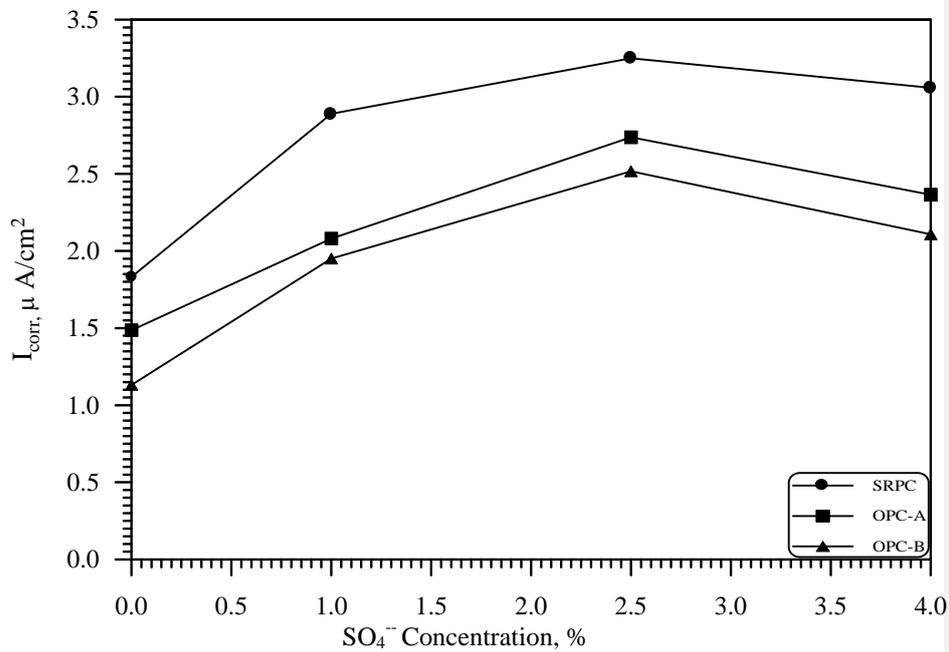


Figure 14: Variation of I_{corr} with sulfate concentration in the concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

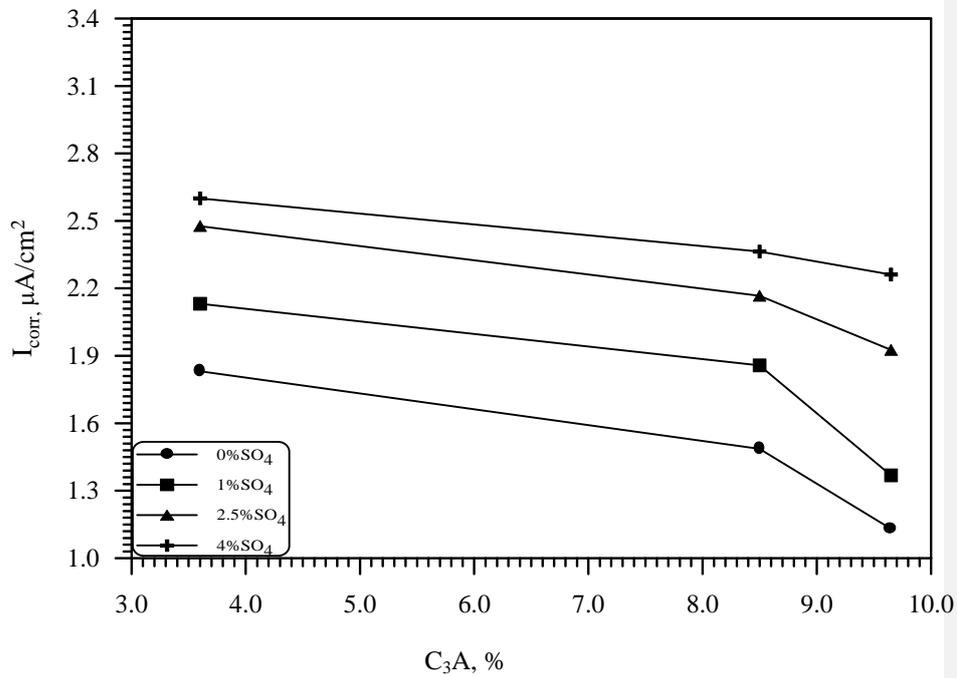


Figure 15: Variation of I_{corr} with C_3A in the concrete specimens exposed to 5% NaCl plus sodium sulfate solution.

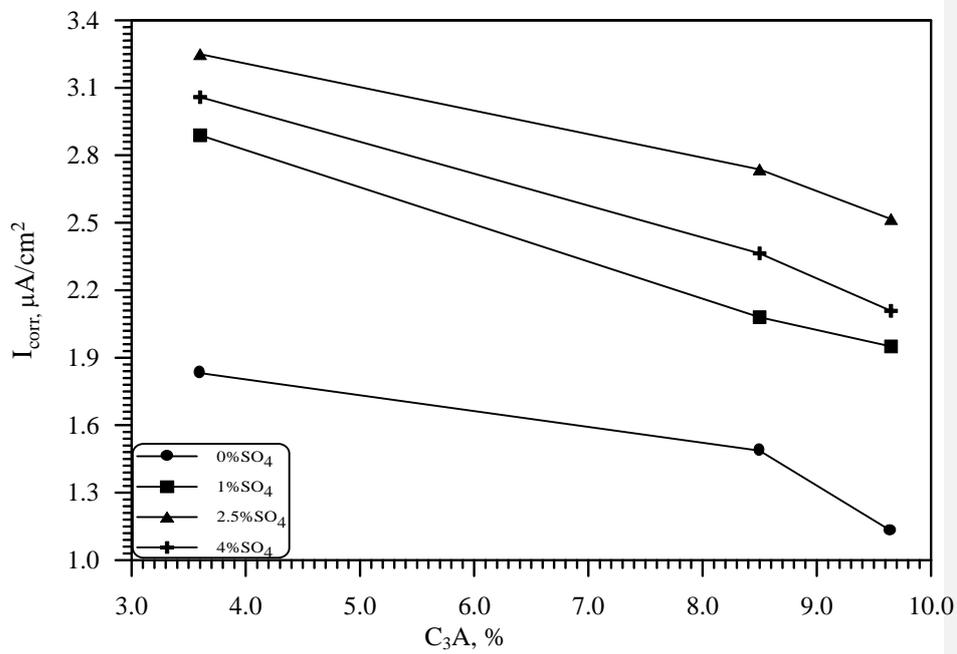


Figure 16: Variation of I_{corr} with C_3A in the concrete specimens exposed to 5% NaCl plus magnesium sulfate solution.

Table 1: Chemical Composition of cements.

| Constituent (Wt %) | SRPC ¹ | OPC-A ² | OPC-B ³ |
|--------------------------------|-------------------|--------------------|--------------------|
| SiO ₂ | 22.00 | 20.52 | 20.00 |
| Al ₂ O ₃ | 4.08 | 5.64 | 6.00 |
| Fe ₂ O ₃ | 4.24 | 3.80 | 3.70 |
| CaO | 64.07 | 64.35 | 65.90 |
| MgO | 2.21 | 2.11 | 0.70 |
| SO ₃ | 1.96 | 2.10 | 2.10 |
| Loss on ignition | 0.80 | 0.70 | 1.30 |
| K ₂ O | 0.31 | 0.36 | - |
| Na ₂ O | 0.21 | 0.19 | - |
| Na ₂ O equivalent | 0.41 | 0.43 | 0.36 |
| C ₃ S | 54.57 | 56.70 | 64.70 |
| C ₂ S | 21.91 | 16.05 | 8.53 |
| C ₃ A | 3.64 | 8.52 | 9.65 |
| C ₄ AF | 12.90 | 11.56 | 11.26 |

¹ Sulfate-resisting Portland cement (C₃A: 3.6%)

² Ordinary Portland cement (C₃A: 8.5%)

³ Ordinary Portland cement (C₃A: 9.65%)

Table 2: Composition of the exposure solutions.

| GROUP | Concentration of the test solution |
|-------|------------------------------------------------------------------------|
| 1 | 5 % NaCl |
| 2 | 5% NaCl + 1% SO_4^{--} (Na_2SO_4 was used) |
| 3 | 5% NaCl + 2.5% SO_4^{--} (Na_2SO_4 was used) |
| 4 | 5% NaCl + 4% SO_4^{--} (Na_2SO_4 was used) |
| 5 | 5% NaCl + 1% SO_4^{--} (MgSO_4 was used) |
| 6 | 5% NaCl + 2.5% SO_4^{--} (MgSO_4 was used) |
| 7 | 5% NaCl + 4% SO_4^{--} (MgSO_4 was used) |

Table 3: Time to initiation of reinforcement corrosion in the concrete specimens exposed to sodium chloride plus sodium sulfate or magnesium sulfate solutions.

| Exposure Solution | Time to initiation of reinforcement corrosion, days | | |
|---------------------------------------------------------------------------------|-----------------------------------------------------|-------|-------|
| | SRPC | OPC-A | OPC-B |
| 5% NaCl | 118 | 132 | 139 |
| 5% NaCl + 1% SO ₄ ²⁻ (Na ₂ SO ₄) | 113 | 117 | 119 |
| 5% NaCl + 2.5% SO ₄ ²⁻ (Na ₂ SO ₄) | 137 | 146 | 148 |
| 5% NaCl + 4% SO ₄ ²⁻ (Na ₂ SO ₄) | 119 | 133 | 131 |
| 5% NaCl + 1% SO ₄ ²⁻ (MgSO ₄) | 111 | 115 | 114 |
| 5% NaCl + 2.5% SO ₄ ²⁻ (MgSO ₄) | 116 | 126 | 131 |
| 5% NaCl + 4% SO ₄ ²⁻ (MgSO ₄) | 127 | 137 | 141 |