



# Corrosion behavior of steel reinforcement in concrete exposed to composite chloride–sulfate environment



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## HIGHLIGHTS

- Corrosion behavior of rebar in concrete was studied against various exposure solutions.
- Determination of corrosion parameters of rebar after exposure to composite solutions.
- Evaluation of effect of various parameters on rebar corrosion by analysis of variance.

## ARTICLE INFO

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## ABSTRACT

The corrosion of steel reinforcement in concrete is the most significant durability problem encountered in reinforced concrete structures. The concomitant presence of sulfate ions may affect chloride induced corrosion of steel reinforcement in concrete. In this paper the outcome of a comprehensive experimental investigation is presented wherein corrosion performance of steel reinforcement in concrete exposed to composite solutions of chloride and sulfate ions has been evaluated. In this investigation, concrete specimens with a centrally embedded steel bar have been prepared from two types of cement namely ordinary Portland cement (OPC) and Portland pozzolana cement (PPC), four w/c ratios and one type of steel reinforcement. The reinforced concrete specimens have been exposed to composite solutions of chloride and sulfate ions of different concentrations. Further in order to evaluate the effect of cation type associated with sulfate ions on corrosion parameters, sodium sulfate and magnesium sulfate were used individually with sodium chloride in the preparation of composite solutions. After exposure, the different corrosion parameters namely half-cell potential, relative resistivity and corrosion current density have been measured. From the results, it was observed that the specimens made with PPC exhibited higher values of relative resistivity and lower values of corrosion density as compared to those made with OPC in all the composite solutions. Further opposite behavior was observed between composite solutions of sodium chloride with magnesium sulfate and sodium chloride with sodium sulfate in terms of variations in relative resistivity and corrosion current density for both OPC and PPC. In addition on the basis of results of analysis of variance, the effect of different parameters on relative resistivity and corrosion current density in composite solutions of sodium chloride and magnesium sulfate and that in composite solutions of sodium chloride and sodium sulfate has also been evaluated.

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## 1. Introduction

Concrete is the most widely produced construction material on earth, with consumption, above dozens of billions of tons [1]. Dense concrete normally possesses excellent strength and durability properties. Because of this, concrete is most widely used for the construction of structures exposed to different types of environment varying from mild to severe. However as demand

for construction in harsh environments increases, the concern towards long service lives of reinforced concrete structures also increases [2]. Under mild environment the exposure conditions include concrete surfaces protected against weather or aggressive conditions; whereas the categories under severe environment include concrete surfaces exposed to severe rain, alternating wetting and drying or occasional freezing or severe condensation and concrete exposed to coastal environment [3]. The exposure conditions under extreme or harsh environment include surface of members in tidal zone, members in direct contact with liquid/solid aggressive chemicals such as chemical and radioactive waste

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### Nomenclature

$i_{\text{corr}}$	corrosion current density	$\beta_a$	anodic Tafel constant
$B$	Stern–Geary constant	$\beta_c$	cathodic Tafel constant
$R_p$	polarization resistance of steel		

containment vessels buried in earth [2,3]. Normally concrete is not free from severe degradation problems. The serviceability limit of reinforced concrete (RC) structures is primarily governed by the extent of damage resulting from service loads and various deterioration processes; those are active throughout the structure's life. Concrete may deteriorate in a number of ways. Apart from structural failures, the significant causes of deterioration and premature failure of reinforced concrete structures are the durability problems. The durability problems can be caused by aggressive external agents namely sulfate ions, chloride ions, atmospheric carbon dioxide, etc. Steel reinforcement corrosion in concrete is the major cause of premature failure of reinforced concrete structures [4]. Thus it is considered as the most significant durability problem encountered in reinforced concrete structures. The faster deterioration of reinforced concrete structures due to corrosion has serious economic and serviceability related problems [5]. It results in huge repair and maintenance cost for the affected structures. Chloride ions are considered to be the primary cause of steel reinforcement corrosion in concrete as compared to other aggressive agents. Chloride ions enter into concrete at the time of its preparation and into the hardened concrete from external environment [6–8]. Chloride ions enter into fresh concrete at the time of its preparation from ingredients such as mixing water, chloride contaminated aggregates and admixtures such as calcium chloride (accelerating admixture); and into hardened concrete by the application of deicing salts in bridge decks and parking structures, from sea water in marine structures, and from soil and ground water contaminated with chloride salts. Chloride introduced into fresh concrete at the time of its preparation is known as internal chloride whereas that enters into hardened concrete is known as external chloride.

In seawater and groundwater, along with chloride salts, sulfate salts are also present. In case of concrete structures exposed to seawater and groundwater, mechanism of deterioration may become even more complex because of ingress of both chloride and sulfate ions. The presence of sulfate ions may influence the chloride attack and likewise the presence of chloride ions may affect the sulfate attack in concrete. These conditions are particularly significant, as in case of seawater the presence of very high concentrations of chloride ions can have a bearing on the effect of sulfate ions [9]. Similarly, groundwater containing sulfate solutions have less concentration of chloride ions as compared to seawater, thereby the mechanism of attack could be different from seawater. From the literature review it is observed that, very limited research have been carried out by researchers on the performance of concrete exposed to composite solutions of chloride and sulfate ions, though performance appraisal of concrete made with different types of binder,  $w/c$  ratio, etc. in chloride solutions and sulfate solutions individually have been reported by several researchers [10–15]. Further studies on corrosion behavior of steel in simulated concrete pore solutions have been carried out by different researchers [16,17]. Similarly Pradhan and Bhattacharjee [18] have studied the corrosion behavior of steel reinforcement in chloride contaminated concrete powder solution extracts. The role of chloride ions in the presence of sulfate ions and that of sulfate ions in the presence of chloride ions on degradation of concrete are not clearly known [19]. Experimental results obtained by Al-Amoudi et al. [20] showed that damage caused by sulfate attack in concrete

is reduced in the presence of chloride ions. Dehwah et al. [7] reported that the presence of sulfate ions in chloride solution did not influence the time to initiation of chloride induced steel reinforcement corrosion but the corrosion rate increased with increase in sulfate ion concentration. Further Zuquan et al. [19] reported that, the presence of sulfate ions in the composite solution increased the resistance to chloride ingress into concrete at early ages but the opposition was observed at latter exposure period. From these limited studies, it is observed that different opinions have been expressed by researchers regarding the performance of concrete in composite solutions of chloride and sulfate salts. Further from the available literature, it is observed that very few studies been carried out on corrosion performance of steel in concrete exposed to composite solutions of chloride and sulfate ions. These few studies include the work carried out by Al-Amoudi and Maslehuddin [21] wherein the authors have carried out a study to investigate the effect of chloride, sulfate and composite chloride and sulfate solutions on corrosion of steel reinforcement in cement paste specimens. Sodium chloride was used as the source of chloride ions and sodium sulfate and magnesium sulfate were used as the source of sulfate ions with each contributing 50% of sulfate concentration. From the measured values of half-cell potential and corrosion current density, it was observed that the corrosion activity was very less in the specimens exposed to only sulfate solution as compared to other solutions. Further the corrosion activity was higher in the specimens exposed to composite chloride–sulfate solutions as compared to those exposed to only chloride solution. Dehwah et al. [7], have carried out an investigation to evaluate the effect of sulfate ion concentration on chloride induced corrosion of steel in concrete made with OPC and SRPC (sulfate resisting Portland cement) and an effective  $w/c$  ratio of 0.45. The reinforced concrete specimens were exposed to chloride and composite solutions of chloride and sulfate solutions. Only one concentration of NaCl and different concentrations of  $\text{Na}_2\text{SO}_4$  and  $\text{MgSO}_4$  were used individually in the preparation of composite solutions. Corrosion parameters namely corrosion potential and corrosion current density were measured at different periods of exposure. The obtained results indicated that chloride induced rebar corrosion rate was more in the specimens exposed to composite solutions of sodium chloride and magnesium sulfate as compared to that in the specimens exposed to composite solutions of sodium chloride and sodium sulfate. Further from this study, observations regarding time to initiation of corrosion and variation in the corrosion rate with sulfate ion concentration are already presented earlier. From these studies, it is observed that reported research is based on exposure of specimens to composite solutions of lesser number of concentrations of chloride and sulfate ions. Further specimens were prepared with lesser number of  $w/c$  ratios. Thus there is a great need to assess the performance of concrete in composite solutions of chloride and sulfate ions of various concentrations and also in concrete prepared with a range of  $w/c$  ratios. Since the microstructure and permeability of concrete depend on  $w/c$  ratios, it is required to observe the variation in ingress of chloride and sulfate ions in concrete prepared different  $w/c$  ratios, which will affect the corrosion parameters. Keeping this in view, in the present work a comprehensive experimental investigation has been carried out wherein the concrete specimens with a

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