Construction and Building Materials 72 (2014) 398-410

Contents lists available at ScienceDirect



Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

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

Bulu Pradhan*

Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India

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

Article history: Received 23 November 2013 Received in revised form 17 September 2014 Accepted 20 September 2014 Available online 10 October 2014

Keywords: Concrete Steel Corrosion Chloride Sulfate

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.

© 2014 Elsevier Ltd. All rights reserved.

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

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

for construction in harsh environments increases, the concern

LS

http://dx.doi.org/10.1016/j.conbuildmat.2014.09.026 0950-0618/© 2014 Elsevier Ltd. All rights reserved.

* Tel.: +91 361 258 2425; fax: +91 361 258 2440.

E-mail addresses: bulu@iitg.ernet.in, bulu.pradhan@gmail.com

B. Pradhan/Construction and Building Materials 72 (2014) 398-410

 β_c

Nomenclature

*i*_{corr} corrosion current density *B* Stern–Geary 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 Zuguan 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 Na₂SO₄ and MgSO₄ 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 chlo-

ride 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

 β_a anodic Tafel constant

cathodic Tafel constant

centrally embedded steel bar were prepared from two types of cement and four w/c ratios and exposed to composite solutions of chloride ions and sulfate ions of varving concentrations with alternate wetting and drying cycles. In addition, for the purpose of evaluating 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. Measurement of half-cell potential, relative resistivity and corrosion current density was carried out on all the specimens at the age of 300 days from the day of preparation. The potential values provide information about the probability of occurrence of steel reinforcement corrosion. Corrosion current density values indicate the extent of corrosion of steel reinforcement and various techniques are used to determine the corrosion current density of steel reinforcement embedded in concrete. Further resistivity of concrete describes electrical resistance and is influenced by the moisture content of concrete and the composition [22]. As reported in literature, there exist a good correlation between the corrosion current density values obtained by linear polarization resistance technique and those obtained by gravimetric (mass loss) measurement [23,24]. The determination of corrosion rate by gravimetric (mass loss) measurement is based on the mass loss of steel bar due to corrosion. In the present study, linear polarization resistance (LPR) technique was used to determine the corrosion current density of steel bar embedded in concrete specimens. Further in the present work, analysis of variance (ANOVA) has been carried out to evaluate the effect chloride ion, sulfate ion, cement type and w/c ratio on the variation of corrosion parameters obtained from the investigation.

2. Experimental work

2.1. Materials

In the present experimental investigation, two types of cement namely ordinary Portland cement (OPC) and Portland pozzolana cement (PPC, fly ash based) and four w/c ratios such as 0.45, 0.50, 0.55 and 0.60 were used in the preparation of concrete specimens. One type of steel such as Tempcore TMT (thermo-mechanically treated) steel bar of diameter 12 mm was used as the steel reinforcement. Coarse aggregates of size 20 mm MSA (maximum size of aggregate) and 12.5 mm MSA were used in the proportion of 66% and 34% of the total mass of coarse aggregate respectively. Locally available sand was used as fine aggregate. The particle size distribution curves of combined coarse aggregate and fine aggregate are shown in Figs. 1 and 2 respectively. Sand is conforming to grading zone-III as per IS 383:1970 [25]. Tap water from laboratory was used for the preparation of test specimens. Concrete mixes for two types of cement at four w/c ratios were designed for similar workability with slump varying from 30 to 50 mm. On the basis of trial tests, a water content of 200 kg/m³ was fixed for the required slump range in all the concrete mixes. The cement content was then calculated by dividing the water content by the w/c ratio. The wet density of concrete was then calculated as per guidelines mentioned in



Fig. 1. Particle size distribution curve for coarse aggregate.



Fig. 2. Particle size distribution curve for sand.

British method of mix design [26]. The wet density of concrete was constant at all w/c ratios. From the known values of wet density, cement content and water content, the aggregate contents were calculated. The cement content, fine aggregate content of the concrete mixes made with OPC and PPC at w/c ratios of 0.45, 0.50, 0.55 and 0.60 are presented in Table 1.

2.2. Test specimens

Cube specimens of size 150 mm were prepared from all the concrete mixes for determination of compressive strength. Slab specimens of size $320 \text{ mm} \times 320 \text{ mm} \times 52 \text{ mm}$ with a centrally embedded steel bar were prepared for measurement of corrosion parameters. The cover to the steel bar was 20 mm both at top and bottom. The slab specimen of this size was selected to accommodate to the size of guard ring assembly which was used in this study for determination of corrosion current density by linear polarization resistance measurement. The slab specimens were prepared from all the concrete mixes for exposure to all the test solutions adopted in the present investigation. It may be noted the wet density of concrete was constant at all w/c ratios. Thus fine aggregate content and coarse aggregate content varied depending on w/c ratio. Total aggregate content increased with increase in w/c ratio. The workability of concrete as indicated by the measured slump values varied with cement paste content and total aggregate content (depending on w/c ratio). The measured slump values were in the range of 30-50 mm. No chemical admixture was used in the preparation of concrete. Concrete cubes and slab specimens with a centrally embedded steel bar were prepared as per the guidelines mentioned in IS 456:2000 [3]. The cube and slab specimens were consolidated by an electrically operated vibrating table during preparation. In order to observe the variation in results between the replicates of the same concrete mix, three replicate slab specimens from some of the concrete mixes were also prepared and exposed to chloride and composite chloride-sulfate solutions of some of the concentrations used in the investigation. In addition for the purpose comparing the variation in corrosion parameters between control mix and those subjected to various exposure solutions, separate specimens were also prepared from both types of cement and four w/c ratios and these specimens were kept in laboratory exposure condition after curing, till the period of testing. After 24 h of preparation, the cube and slab specimens were demoulded and subjected to moist curing in a curing tank for 27 days. After completion of moist curing the specimens were removed from the curing tank. The schematic diagram of the slab specimen is shown in Fig. 3.

2.3. Exposure conditions

The concrete specimens were exposed to solutions of chloride ions and composite solutions of chloride and sulfate ions. The chloride solutions were prepared by of adding different concentrations of sodium chloride (NaCl) in required quantity of water, as it is the most commonly encountered source of chloride. The composite solutions were prepared by adding sodium chloride and magnesium sulfate (MgSO₄) and sodium chloride and sodium sulfate (Na₂SO₄) in the water. Magnesium sulfate and sodium sulfate are selected as the source of sulfate ions as the sulfates found in groundwater and seawater are mostly in the form of these compounds. In addition, use of two different sulfate salts (MgSO₄ and Na₂SO₄) in the present investigation is to evaluate the effect of associated cation type with sulfate ions on chloride induced corrosion of steel in concrete. Sodium chloride, magnesium sulfate and sodium sulfate of analytical reagent grade were used in the preparation of test solutions. Sodium chloride, sodium sulfate and magnesium sulfate are normally present in seawater and in contaminated soil and groundwater. In addition it may be noted that the reported research in literature by different

Table 1Concrete mix quantities.

OPC and PPC 0.45 444.44 605.69 1124.86 0.50 400.00 621.25 1153.75 0.55 363.64 633.98 1177.39 0.60 333.33 644.58 1197.08	Cement type	water/cement (w/c) ratio	Cement content (kg/m ³)	Fine aggregate content (kg/m ³)	Coarse aggregate content (kg/m ³)
0.00 555.55 07.70 1157.00	OPC and PPC	0.45 0.50 0.55 0.60	444.44 400.00 363.64 333.33	605.69 621.25 633.98 644.58	1124.86 1153.75 1177.39 1197.08



both at top and bottom

Fig. 3. Slab specimen.

researchers [7,19] indicate the use of these salts as sources of chloride and sulfate ions in their investigation. Since these salts are present in varying concentrations in groundwater and seawater and also keeping in view the concentrations of these salts used by different researchers as observed from literature, the different concentrations of sodium chloride, sodium sulfate and magnesium sulfate are taken in the present investigation. Sodium chloride concentrations of 1.5%, 3.5% and 5% (by mass of water) were added for preparation chloride solutions. Magnesium sulfate and sodium sulfate concentrations each of 2.5% and 5% (by mass of water) were added along with above concentrations of sodium chloride for the preparation of composite solutions. The details about the test solutions used in the present investigation are presented in Table 2.

The slab specimens having a centrally embedded steel bar and prepared from different concrete mixes were exposed to chloride and composite solutions with alternate wetting-drying cycles. After removal from curing tank (after 27 days of moist curing), the slab specimens were kept in laboratory exposure condition for

Table	2
-------	---

Details of test solution	ons.
--------------------------	------

Test solution	Concentration of solutions	Туре
1	1.5% NaCl	Chloride solutions
2	3.5% NaCl	
3	5% NaCl	
4	1.5% NaCl + 2.5% MgSO4	Composite solutions
5	1.5% NaCl + 5% MgSO ₄	
6	1.5% NaCl + 2.5% Na ₂ SO ₄	
7	1.5% NaCl + 5% Na ₂ SO ₄	
8	3.5% NaCl + 2.5% MgSO ₄	
9	3.5% NaCl + 5% MgSO ₄	
10	3.5% NaCl + 2.5% Na ₂ SO ₄	
11	3.5% NaCl + 5% Na ₂ SO ₄	
12	5% NaCl + 2.5% MgSO ₄	
13	5% NaCl + 5% MgSO ₄	
14	5% NaCl + 2.5% Na ₂ SO ₄	
15	5% NaCl + 5% Na ₂ SO ₄	

a period of fourteen days. After that the slab specimens were exposed to different test solutions. For this purpose replicate specimens from the same concrete mix were used separately for exposure to chloride solutions and composite solutions. The alternate wetting and drying cycles comprised of seven days of immersion of slab specimens in chloride and composite solutions in plastic tanks followed by seven days of laboratory drying. The exposure to test solutions with wetting–drying cycles was continued up to 300 days from the day of preparation of specimens. All the chloride solutions and composite solutions of chloride and sulfate ions were replenished periodically.

2.4. Compressive strength test

After completion of moist curing, the compressive strength of cube specimens prepared from two types of cement and four w/c ratios was determined at the age of 28 days in the compression testing machine. The values of 28-day compressive strength of concrete mixes prepared from different w/c ratios were determined to know the range of compressive strength of concrete made with OPC and PPC. In this study the behavior of reinforced concrete specimens made from concrete mixes of these compressive strength values was studied after exposure to chloride solutions of chloride and sulfate ions.

2.5. Measurement of corrosion parameters

The corrosion parameters such as half-cell potential, relative resistivity and corrosion current density were measured on all the slab specimens at the age of 300 days from the day of preparation using the corrosion monitoring instrument (Make ACM, Gill AC serial no. 1542). The testing age of 300 days was selected so as to subject the slab specimens to exposure solutions for a sufficient period of time with alternate wetting and drying cycles and to observe the corrosion behavior of rebar in concrete after exposure to chloride and composite chloride-sulfate solutions of varying concentrations. Corrosion current density was determined by linear polarization resistance (LPR) technique. Saturated calomel electrode (SCE) was used as reference electrode for measurement of half-cell potential of the steel bar embedded in the slab specimen. The LPR test with IR compensation was performed with guard ring arrangement on the slab specimens of control mix and those exposed to test solutions (i.e. chloride and composite chloride-sulfate solutions). The function of guard ring (secondary auxiliary electrode) is to maintain the confinement current, that prevents the perturbation current applied through the auxiliary electrode (present in the guard ring assembly) spreading beyond a known area. Thus known value of polarized length of steel bar is used in the calculation of corrosion current density, which is determined by dividing the corrosion current with the polarized surface area of the steel bar. While determining the corrosion current density, the IR drop value in the cover concrete has to determined and compensated. This is required, as concrete is a high resistive medium, thus IR drop in cover concrete has to be compensated while determining the corrosion current density. IR represents the ohmic potential drop that occurs between the working electrode and the reference electrode. 'I' and 'R' represent current and ohmic resistance respectively. Before placing the guard ring assembly on the surface of slab specimen, conducting sponge attached to the guard ring was wetted with soap solution so as to have proper electrical contact. For determination of corrosion current density, the polarized surface area of the steel bar is taken as the area lying under a circle intersecting the midpoint between the two sensor electrodes [27] present in guard ring assembly and only top half surface area of the steel bar is assumed to be polarized [28]. In the linear polarization resistance technique, the steel bar in the slab specimen was polarized to ±20 mV from the equilibrium potential at a scan rate of 0.1 mV per second.

Using the Stern–Geary equation, the corrosion current density i_{corr} , is obtained as follows;

$$rr = B/R_p \tag{1}$$

where B = Stern–Geary constant; R_p = polarization resistance of steel. The expression for Stern–Geary constant is given by;

 i_{co}

$$B = \frac{(\beta_a \times \beta_c)}{2.3(\beta_a + \beta_c)} \tag{2}$$

where β_a and β_c are anodic and cathodic Tafel constants respectively. The value of *B* is considered as 26 mV for steel bar in active condition [6,7,23,29].

دائلو دکننده مقالات علم FREE دانلو دکننده مقالات علم

401

3. Results and discussion

3.1. Compressive strength

As already stated, the 28 day compressive strength of concrete was determined in the compression testing machine. The compressive strength values of concrete made with OPC were found to be 37.63 N/mm², 34.96 N/mm², 29.78 N/mm² and 25.33 N/mm² at *w/c* ratios of 0.45, 0.50, 0.55 and 0.60 respectively. Similarly the compressive strength values of PPC concrete were 38.52 N/mm², 37.48 N/mm², 34.22 N/mm² and 27.41 N/mm² at *w/c* ratios of 0.45, 0.50, 0.55 and 0.60 respectively. From these results it is observed that concrete made with PPC showed higher compressive strength as compared to that made with OPC at all *w/c* ratios. This is due to the production of additional C–S–H gel by pozzolanic reaction in concrete mixes made with PPC. Further the compressive strength values decreased with increase in *w/c* ratio.

3.2. Potential value

The plot of half-cell potential values (with respect to saturated calomel electrode) of the steel bar embedded in the slab specimens and kept in laboratory exposure condition (control mix) at different w/c ratios for OPC and PPC is shown in Fig. 4. The half-cell potential values of the steel bar embedded in the slab specimens and exposed to composite solutions of chloride and sulfate ions at different w/c ratios are shown in Figs. 5–7 for specimens made with OPC and in Figs. 8–10 for specimens made with PPC. Similarly plots of half-cell potential vs. w/c ratio for specimens exposed to sodium chloride solution only are shown in Figs. 11 and 12 for OPC and PPC respectively. In these figures the terms 'NC', 'MS' and 'NS' represent sodium chloride, magnesium sulfate and sodium sulfate respectively. From these figures (Figs. 5-12) it is observed that, irrespective of cement type, w/c ratio, chloride ion concentration, sulfate ion concentration and associated cation type, the potential values were more negative than -270 mV (SCE)/-350 mV (Cu/CuSO₄ electrode), that corresponds to greater than 90% probability of occurrence of steel reinforcement corrosion as per ASTM C876 [30]. Thus it indicates initiation of steel reinforcement corrosion with greater probability in all exposure solutions. Further it is observed that there is no systematic variation in half-cell potential values with w/c ratio at different concentrations of chloride and sulfate ions (both magnesium sulfate and sodium sulfate) for both types of cement. It may be noted that potential values can be more negative than -270 mV (SCE)/ -350 mV (Cu/CuSO₄ electrode) without significant presence of



Fig. 4. Half-cell potential vs. w/c ratio in control concrete mix.



Fig. 5. Half-cell potential vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 6. Half-cell potential vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 7. Half-cell potential vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

corrosion and this is due to polarization phenomena induced by limited oxygen diffusion [1,10]. Thus potential values may not be sufficient to evaluate the corrosion behavior. In control mix, the potential values were more positive than -270 mV (SCE) for both types of cement and at all w/c ratios as observed from Fig. 4. This



Fig. 8. Half-cell potential vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 9. Half-cell potential vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 10. Half-cell potential vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

indicates lower probability of occurrence of steel reinforcement corrosion in the control mix. From Figs. 5–10 it is inferred that, the specimens exposed to composite solutions of sodium chloride and sodium sulfate mostly exhibited less negative potential as compared to those exposed to composite solutions of sodium



Fig. 11. Half-cell potential vs. *w*/*c* ratio for OPC exposed to sodium chloride solutions.



Fig. 12. Half-cell potential vs. w/c ratio for PPC exposed to sodium chloride solutions.

chloride and magnesium sulfate for both types of cement. It may be due to the reduction in concentration of iron ions in the electrolytic pore solution of the concrete [12], which is exposed to composite solutions of sodium chloride and sodium sulfate. The halfcell potential values mostly decreased with increase in sodium chloride concentration for both types of cement as observed from Figs. 11 and 12.

3.3. Relative resistivity

The measured IR compensation value which is obtained by dividing the IR drop value across the cover concrete within the confined area of the guard ring with the corrosion current density represents the relative resistivity of the cover concrete. The IR compensation values of the specimens exposed to different solutions and also of control mix were determined at the age of three hundred days. The plot of relative resistivity (in Ohm cm²) of specimens kept in laboratory exposure condition (control mix) at different w/c ratios for OPC and PPC is shown in Fig. 13. The plots of relative resistivity (in Ohm cm²) of concrete exposed to composite solutions of chloride and sulfate ions at different w/c ratios are presented in Figs. 14-16 for specimens made with OPC and in Figs. 17-19 for specimens made with PPC. From these figures it is observed that the resistivity values mostly increased with decrease in w/c ratio for both types of cement in control mix and also in the specimens subjected to exposure solutions. In few cases, higher value of relative resistivity was observed at higher w/c ratio as compared to that at lower w/c ratio. This may be possibly due to دائلو دکننده مقالات علم FRE دائلو دکننده مقالات علم



Fig. 13. Relative resistivity of control mix for OPC and PPC at different w/c ratios.



Fig. 14. Relative resistivity at different w/c ratios for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 15. Relative resistivity at different w/c ratios for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

lower moisture content in the cover concrete at higher w/c ratio as compared to that at lower w/c ratio and as concrete is a heterogeneous composite, this local alteration in moisture content might have resulted in a increase in concrete resistivity at higher w/c ratio than that at lower w/c ratio. As observed from Table 1, the



Fig. 16. Relative resistivity at different w/c ratios for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 17. Relative resistivity at different w/c ratios for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 18. Relative resistivity at different w/c ratios for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

cement-to-aggregate ratio decreases with increase in w/c ratio. The concrete mix made with lower w/c ratio exhibits denser microstructure due to production of more C–S–H gel as result of higher cement content as compared to the concrete mix made with higher



Fig. 19. Relative resistivity at different w/c ratios for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

w/c ratio. Due to the difference in denseness of microstructure, the penetration of chloride ions and sulfate ions into concrete is different at different w/c ratios. This is reflected in the values of relative resistivity of concrete, as specimens made with lower w/c ratio exhibited higher values of relative resistivity as compared to those made with higher w/c ratios. Further the specimens made with PPC showed higher value of relative resistivity as compared to those made with OPC in all exposure solutions and also in control mix. This is due to formation of denser microstructure as result of production of additional C-S-H gel due to pozzolanic reaction in concrete made with PPC as compared to that made with OPC and thus lowering the penetration of aggressive ions in the concrete made with PPC. On comparison between control mix and those exposed to composite chloride-sulfate solutions, it is observed that there is no systematic variation in of relative resistivity values. This may attributed to the effect of variation in moisture content in control mix and in the specimens exposed to these solutions; and also due to the effect of formation of expansive products in the specimens exposed to these solution, thereby altering the resistivity of concrete.

From Figs. 14–16, it is observed that the OPC specimens exposed to magnesium sulfate solutions exhibited higher values of relative resistivity as compared to those exposed to sodium sulfate solutions at all concentrations of sodium chloride and at all w/c ratios incorporated in the study. However the opposition was observed for specimens made from PPC, i.e. PPC specimens subjected to sodium sulfate solutions showed higher values of relative resistivity as compared to those subjected to magnesium sulfate solutions at all chloride concentrations as observed from Figs. 17-19. This may be attributed to the fact that for OPC specimens exposed to composite solutions of sodium chloride and magnesium sulfate, there is comparatively higher production of magnesium hydroxide (brucite) due to the reaction between calcium hydroxide (portlandite) and magnesium sulfate and thus resulting in higher resistivity due to filling of pores with magnesium hydroxide. It may be noted here that, calcium hydroxide acts as the first defensive material to react with magnesium sulfate [31] and thus act as retarder to the attack of magnesium and sulfate ions on C-S-H gel. Rasheeduzzafar et al. [32] have carried out XRD and SEM analysis on cement paste specimens after an exposure of 2 years in mixed magnesium-sodium sulfate solutions. The results of XRD and SEM analysis indicated the formation of brucite in ordinary Portland cement whereas relatively marginal quantity of brucite was formed in fly ash blended cement. Further, XRD and SEM analysis from this study also indicated the reduction in portlandite in plain and blended cements due to formation of gypsum. For OPC specimens exposed to composite solutions of sodium chloride and sodium sulfate (Figs. 14-16), formation of more amount of gypsum and ettringite might have resulted in lower relative resistivity as result of less denser microstructure. For PPC specimens exposed to composite solutions of sodium chloride and magnesium sulfate (Figs. 17–19), the lower relative resistivity may be attributed to the decrease in calcium hydroxide (that acts as the first defensive material to react with magnesium sulfate) content as a result of consumption in pozzolanic reaction and due to formation of gypsum. Due to reduction in calcium hydroxide content in PPC, the reaction of magnesium and sulfate ions with C-S-H gel leads to the formation of gypsum and noncementitious M-S-H (magnesium silicate hydrate) [31] and this effect is possibly more dominant than more production of C-S-H gel and thereby lowering the relative resistivity of concrete. Similarly for specimens made from PPC and subjected to composite solutions of sodium chloride and sodium sulfate (Figs. 17-19), the higher relative resistivity may be due to reduction in the formation of gypsum and ettringite due to less availability of calcium hydroxide and C₃A respectively in PPC and due to formation of denser structure as result of production of additional C-S-H gel due to pozzolanic reaction [31].

The variation in relative resistivity with sulfate ion concentration is mostly not systematic in both types of composite solutions as observed Figs. 14–19. The plots of relative resistivity of concrete specimens exposed to chloride solution only are shown in Figs. 20 and 21 for OPC and PPC respectively. From Fig. 20, it is noted that for OPC, the resistivity mostly decreased with increase in chloride ion concentration. For PPC, mostly there was no systematic variation in relative resistivity with chloride ion concentration as observed from Fig. 21, however highest and lowest value of resistivity were observed at exposure to sodium chloride concentrations of 1.5% and 5% respectively. From Figs. 14-16 and 20, it is observed that the OPC specimens exposed to composite solutions of sodium chloride and magnesium sulfate showed higher values of relative resistivity as compared to those exposed to only sodium chloride solution. However opposition was observed in case of OPC specimens exposed to composite solutions of sodium chloride and sodium sulfate, i.e. resistivity was more in specimens subjected to sodium chloride solution only as compared to that in composite solutions of sodium chloride and sodium sulfate. In composite solutions of sodium chloride and magnesium sulfate, the presence of chloride ions may not have affected the formation of brucite significantly at all concentrations of sodium chloride used in the study and thus exhibiting higher relative resistivity in OPC specimens as compared to that in only sodium chloride solution



Fig. 20. Relative resistivity at different w/c ratios for OPC exposed to sodium chloride solutions.



Fig. 21. Relative resistivity at different w/c ratios for PPC exposed to sodium chloride solutions.

wherein the presence of chloride ions increased the conductivity of concrete, thereby lowering the relative resistivity of concrete. The lower resistivity of OPC specimens in composite solutions of sodium chloride and sodium sulfate as compared to that in chloride solution only may be due to increase in conductivity of concrete in the presence of chloride ions along with the formation of gypsum and ettringite.

From Figs. 17–19 and 21, it is noted that the PPC specimens in composite solutions of sodium chloride and sodium sulfate mostly showed higher values of relative resistivity as compared to those exposed to only sodium chloride solution whereas the PPC specimens in composite solutions of sodium chloride and magnesium sulfate showed lower values of relative resistivity as compared to those exposed to only sodium chloride solution. This is due to the fact that the effect of formation of additional C-S-H gel was more dominant than the increase in conductivity of concrete in the presence of chloride ions, thereby resulting in higher resistivity for PPC in composite solutions of sodium chloride and sodium sulfate as compared to that exposed to only sodium chloride solution. The lower resistivity of PPC in composite solutions of sodium chloride and magnesium sulfate as compared to that in only sodium chloride solution is attributed to the combined effect of formation of gypsum and non-cementitious magnesium silicate hydrate along with the effect of conductivity in the presence of chloride ions, thereby lowering the relative resistivity.

3.4. Corrosion current density

The plot of corrosion current density (in $\mu A/cm^2$) of the specimens kept in laboratory exposure condition (control mix) at different w/c ratios for OPC and PPC is shown in Fig. 22. The results of corrosion current density of steel reinforcement in the specimens exposed to composite solutions of chloride and sulfate ions at different w/c ratios are shown in Figs. 23-25 for OPC concrete specimens and in Figs. 26-28 for specimens made with PPC. Further the plots of corrosion current density at different w/c ratios for specimens exposed to sodium chloride solution only are shown in Figs. 29 and 30 for OPC and PPC specimens respectively. From the obtained results it was observed that, the difference in corrosion current density values between the average value of three replicates and the individual replicate value of the same concrete mix is little. The same was also observed in half-cell potential and relative resistivity values.

From Figs. 22–30, it is found that the specimens made from PPC showed lower values of corrosion current density as compared to those made from OPC in all exposure solutions and at all w/c ratios.



دائلو دکننده مقالات علم FREE reepaper.me

Fig. 22. Corrosion current density in control mix for both types of cement and different w/c ratios.



Fig. 23. Corrosion current density vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 24. Corrosion current density vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

This is due to the formation of denser microstructure in the specimens made with PPC than that in OPC, thus resulting in higher resistivity of concrete and significantly retarding the diffusion of



Fig. 25. Corrosion current density vs. w/c ratio for OPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 26. Corrosion current density vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 1.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 27. Corrosion current density vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 3.5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).

oxygen to the steel reinforcement level in concrete. On an average, corrosion current density of OPC specimens was about 1.01–1.43 times that of PPC specimens in composite solutions of sodium chloride and magnesium sulfate whereas in composite solutions of sodium chloride and sodium sulfate, corrosion current density of OPC specimens was about 1.46–1.87 times that of PPC



Fig. 28. Corrosion current density vs. w/c ratio for PPC exposed to composite solutions of sulfate ions (MgSO₄ and Na₂SO₄) with 5% sodium chloride (NC: sodium chloride, MS: magnesium sulfate and NS: sodium sulfate).



Fig. 29. Corrosion current density vs. *w*/*c* ratio for OPC exposed to sodium chloride solutions.



Fig. 30. Corrosion current density vs. w/c ratio for PPC exposed to sodium chloride solutions.

specimens. Further it is observed that the corrosion current density mostly increased with increase in w/c ratio in different exposure solutions for both types of cement. However the variation was not as systematic as that for relative resistivity with w/c ratio. In some cases the opposite trend in corrosion current density was observed at different w/c ratios. This opposite trend is possibly due to the alteration in moisture content in the cover concrete that might have changed the conductivity of concrete. As concrete is a

407

دائلو دکننده مقالات علم reepaper.me heterogeneous material, this local alteration in conductivity of concrete might have resulted in an opposite variation in corrosion current density values at these w/c ratios.

From Figs. 29 and 30, it is inferred that corrosion current density values increased with increase in sodium chloride concentration in both types of cement and this is due to increase in conductivity of concrete in the presence of higher amount of chloride ions at the rebar level. On comparison of corrosion current density between control concrete mix and those exposed to chloride and composite chloride–sulfate solutions, it is observed that control mix specimens exhibited lower values of corrosion current density as compared those subjected to various exposure solutions.

From Figs. 23–25, it is observed that the OPC specimens exposed to composite solutions of sodium chloride and magnesium sulfate mostly showed lower values of corrosion current density as compared to those exposed to composite solutions of sodium chloride and sodium sulfate. This is attributed to increase in resistivity of OPC concrete in composite solutions of sodium chloride and magnesium sulfate due to filling of pores with magnesium hydroxide as compared to lower resistivity of OPC in composite solutions of sodium chloride and sodium sulfate due to formation of more amount of gypsum and ettringite.

From Figs. 26–28, it is found that specimens made with PPC mostly exhibited lower values of corrosion current density in composite solutions of sodium chloride and sodium sulfate as compared to those exposed to composite solutions of sodium chloride and magnesium sulfate. The lower corrosion current density of PPC in composite solutions of sodium chloride and sodium sulfate may be due to higher resistivity as result of reduction in formation of gypsum and ettringite as compared to lower resistivity of PPC concrete in composite solutions of sodium chloride and magnesium sulfate due to the formation gypsum and noncementitious magnesium silicate hydrate.

Further From Figs. 23–25 and 29, it is observed that, OPC specimens exposed to composite solutions of sodium chloride and magnesium sulfate mostly showed lower values of corrosion current density as compared to those exposed to only sodium chloride solution. However opposition was observed for OPC specimens exposed to composite solutions of sodium chloride and sodium sulfate, i.e. corrosion current density was mostly higher in specimens subjected to composite solutions of sodium chloride and sodium sulfate as compared to that in only sodium chloride solution. From Figs. 26–28 and 30, it is found that the PPC specimens in composite solutions of sodium chloride and magnesium sulfate mostly showed higher values of corrosion current density

as compared to that in only sodium chloride solution whereas PPC specimens in composite solutions of sodium chloride and sodium sulfate mostly resulted in lower values of corrosion current density as compared to those exposed to only sodium chloride solution. The variations in corrosion current density in specimens made with both OPC and PPC in above exposure solutions are due to variations in resistivity of concrete and the reasons for variations in resistivity of concrete in different exposure solutions are already stated earlier. Further it is noted that there is no systematic variation in corrosion current density with concentration of sulfate ions incorporated in the study for both types of composite solutions.

From the aforementioned discussions on obtained results, it is observed that the relative resistivity and corrosion current density of steel in concrete specimens subjected to different exposure solutions varied with w/c ratio as the ingress of chloride ions and sulfate ions varied depending on the permeability of concrete. Thus the extent of reactions taking place on the steel surface in the presence of chloride ions and the change in microstructure of concrete due to the reactions of chloride and sulfate ions with hydrated cement products may be affected by the extent of penetration of these ions, which is influenced by permeability of concrete that depends on w/c ratio. In some cases, opposite trend in relative resistivity and corrosion current density was observed at different w/c ratios in different exposure solutions.

The results of corrosion parameters obtained from this investigation provide information about the corrosion behavior of reinforced concrete exposed to external chloride and composite chloride–sulfate solutions of known concentrations for a certain period of time.

3.5. Analysis of variance for relative resistivity and corrosion current density

For the purpose of analyzing the effect of different factors on the variation of relative resistivity and corrosion current density of steel reinforcement in concrete exposed to composite solutions of different concentrations of chloride and sulfate ions, the analysis of variance (ANOVA) calculation was carried out as per the guide-lines presented by Hicks [33], The relative resistivity and corrosion current density values of specimens for two types of cement, four *w/c* ratios at different concentrations of sodium chloride and magnesium sulfate and those at different concentrations of sodium chloride and sodium sulfate were tabulated separately for relative resistivity and corrosion current density. The total sum of squares was calculated, which is divided into the sum of squares (SS) for individual factors and that for the residual random error. Mean

Tal	hl	Р	32
Id	U	C	30

Analysis of variance results for relative resistivity in composite solutions of sodium chloride and magnesium sulfate.

Source	Level	Degree of freedom (df)	Sum of squares (SS)	Mean squares (MS)	F-ratio	'F from Fisher's distribution at 95% probability
Cement type	2	1	1.013×10^{10}	1.013×10^{10}	871.145	4.08
w/c ratio	4	3	$2.077 imes 10^9$	6.923×10^{8}	59.535	2.84
Chloride ion concentration	3	2	$1.178 imes 10^8$	$5.891 imes 10^7$	5.066	3.23
Sulfate ion concentration	2	1	2.856×10^7	2.856×10^{7}	2.456	4.08
Error		40	$4.652 imes 10^8$	$1.163 imes 10^7$		
Total		47	1.282×10^{10}			

Ta	ble	3b	•

Analysis of variance results for relative resistivity in composite solutions of sodium chloride and sodium sulfate.

Source	Level	Degree of freedom (df)	Sum of squares (SS)	Mean squares (MS)	F-ratio	'F' from Fisher's distribution at 95% probability
Cement type	2	1	$\textbf{4.936}\times \textbf{10}^{10}$	$\textbf{4.936}\times \textbf{10}^{10}$	1117.976	4.08
w/c ratio	4	3	$2.053 imes 10^9$	6.843×10^8	15.497	2.84
Chloride ion concentration	3	2	$\textbf{7.286}\times 10^7$	$3.643 imes 10^7$	0.825	3.23
Sulfate ion concentration	2	1	1.501×10^{5}	1.501×10^{5}	0.003	4.08
Error		40	1.766×10^9	$4.416 imes 10^7$		
Total		47	5.326×10^{10}			

Table 4a															
Analysis of variance results f	or corr	osio	n currei	nt densi	ty ir	n compo	osite	solutions	of sodiur	n chlor	ide and	magnes	ium	sulfa	te.
			_				-					4	_		

Source	Level	Degree of freedom (df)	Sum of squares (SS)	Mean squares (MS)	F-ratio	'F' from Fisher's distribution at 95% probability
Cement type	2	1	16.532	16.532	7.231	4.08
w/c ratio	4	3	406.862	135.621	59.319	2.84
Chloride ion concentration	3	2	21.40	10.70	4.68	3.23
Sulfate ion concentration	2	1	1.138	1.138	0.498	4.08
Error		40	91.452	2.286		
Total		47	537.384			

Table 4b

Analysis of variance results for corrosion current density in composite solutions of sodium chloride and sodium sulfate.

Source	Level	Degree of freedom (df)	Sum of squares (SS)	Mean squares (MS)	F-ratio	'F from Fisher's distribution at 95% probability
Cement type	2	1	174.159	174.159	89.360	4.08
w/c ratio	4	3	342.943	114.314	58.654	2.84
Chloride ion concentration	3	2	14.454	7.227	3.708	3.23
Sulfate ion concentration	2	1	3.040	3.040	1.560	4.08
Error		40	77.958	1.949		
Total		47	612.554			

squares (MS) of the factors were then calculated by dividing their corresponding sum of squares by the associated degrees of freedom (df). The effect of individual factors on relative resistivity and corrosion current density was then estimated by testing the hypothesis of equality of variances, which is the test of null hypothesis or simply the significance test at a particular probability level. For obtaining this, the F-statistic which is the ratio of mean squares of different factors to the mean squares of the residual error was calculated and then compared with the tabulated Fvalues related to Fisher distribution. The F-values related to Fisher distribution depending on number of degrees of freedom of individual factors and that of residual error at a probability level are available in relevant texts [33]. The results of analysis of variance for relative resistivity for composite solutions of sodium chloride and magnesium sulfate and that for composite solutions of sodium chloride and sodium sulfate are presented in Tables 3a and 3b respectively. Similarly the results of analysis of variance for corrosion current density are presented in Tables 4a and 4b for composite solutions of sodium chloride and magnesium sulfate and sodium chloride and sodium sulfate respectively. From Tables 3a and 4a, it is observed that, all the factors except concentration of sulfate ions are affecting both relative resistivity and corrosion current density in composite solutions of sodium chloride and magnesium sulfate, as the estimated F-values are higher than the tabulated F-values at 95% confidence level. Further from Table 3b, it is inferred that cement type and w/c ratio are only affecting relative resistivity of concrete in composite solutions of sodium chloride and sodium sulfate whereas all the factors except concentration of sulfate ions are affecting corrosion current density as observed from Table 4b.

4. Conclusions

From the results of the present study, the following conclusions were obtained;

- (i) The half-cell potential values were more negative than $-270 \text{ mV} \text{ (SCE)}/-350 \text{ mV} \text{ (Cu/CuSO}_4 \text{ electrode)}$ for both types of cement at all *w/c* ratios and in all exposure solutions, thus indicating the initiation of steel reinforcement corrosion in concrete.
- (ii) 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 exposure solutions at all w/c ratios.

- (iii) The specimens made with OPC showed higher values of relative resistivity and lower values of corrosion current density in composite solutions of sodium chloride and magnesium sulfate whereas opposite behavior was observed for OPC in composite solutions of sodium chloride and sodium sulfate.
- (iv) PPC exhibited lower values of relative resistivity and higher values of corrosion density when exposed to composite solutions of sodium chloride and magnesium sulfate whereas it showed opposite behavior in composite solutions of sodium chloride and sodium sulfate.
- (v) The variations in relative resistivity and corrosion current density between composite solutions of sodium chloride with magnesium sulfate and sodium chloride solution; and that between composite solutions of sodium chloride with sodium sulfate and sodium chloride solution were mostly opposite for both OPC and PPC.
- (vi) From the results of analysis of variance it is found that except concentration of sulfate ions; cement type, w/c ratio and chloride ion concentration are affecting both relative resistivity and corrosion current density in composite solutions of sodium chloride and magnesium sulfate. In composite solutions of sodium chloride and sodium sulfate, chloride ions and sulfate ions did not have significant effect on the variations in relative resistivity, however chloride ion concentration along with cement type and w/c ratio have significant effect on corrosion current density of steel in concrete.

Acknowledgements

The present work is a part of the sponsored research project funded by Department of Science and Technology, Government of India. The author wishes to express his gratitude to Department of Science and Technology, Government of India for funding the project through Fast Track scheme for Young Scientists.

References

- Montemor MF, Simoes AMP, Ferreira MGS. Chloride-induced corrosion on reinforcing steel: from the fundamentals to the monitoring techniques. Cem Concr Compos 2003;25:491–502.
- [2] Monteiro PJM, Kurtis KE. Time to failure for concrete exposed to severe sulfate attack. Cem Concr Res 2003;2003(33):987–93.
- [3] IS 456-2000. Plain and reinforced concrete code of practice. New Delhi: Bureau of Indian Standards.
- [4] Li CQ, Zheng JJ, Lawanwisut W, Melchers RE. Concrete delamination caused by steel reinforcement corrosion. J Mater Civ Eng ASCE 2007;19:591–600.

دانلو دکننده مقالات علم Freepaper.me pa

- [5] Alhozaimy A, Hussain RR, Al-Zaid R, Al Negheimish A. Investigation of severe corrosion observed at intersection points of steel rebar mesh in reinforced concrete construction. Constr Build Mater 2012;37:67–81.
- [6] Saricimen H, Mohammad M, Quddus A, Shameem M, Barry MS. Effectiveness of concrete inhibitors in retarding rebar corrosion. Cem Concr Compos 2002;24:89–100.
- [7] Dehwah HAF, Maslehuddin M, Austin SA. Long-term effect of sulfate ions and associated cation type on chloride-induced reinforcement corrosion in Portland cement concretes. Cem Concr Compos 2002;24:17–25.
- [8] Arya C, Xu Y. Effect of cement type on chloride binding and corrosion of steel in concrete. Cem Concr Res 1995;25:893–902.
- [9] Santhanam M, Cohen M, Olek J. Differentiating seawater and groundwater sulfate attack in Portland cement mortars. Cem Concr Res 2006;36:2132–7.
- [10] Choi YS, Kim JG, Lee KM. Corrosion behavior of steel bar embedded in fly ash concrete. Corros Sci 2006;48:1733–45.
- [11] Al-Akhras NM. Durability of metakaolin concrete to sulfate attack. Cem Concr Res 2006;36:1727–34.
- [12] Pradhan B, Bhattacharjee B. Role of steel and cement type on chloride induced corrosion in concrete. ACI Mater J 2007;104:612–9.
- [13] Al-Dulaijan SU. Sulfate resistance of plain and blended cements exposed to magnesium sulfate solutions. Constr Build Mater 2007;21:1792–802.
- [14] Sakr K. Effect of cement type on the corrosion performance of reinforcing steel bars exposed to acidic media using electrochemical techniques. Cem Concr Res 2005;35:1820–6.
- [15] Dhir RK, Jones MR, McCarthy MJ. PFA concrete: chloride-induced reinforcement corrosion. Mag Concr Res 1994;46:269–77.
- [16] Moreno M, Morris W, Alvarez MG, Duffo GS. Corrosion of reinforcing steel in simulated concrete pore solutions: effect of carbonation and chloride content. Corros Sci 2004;46:2681–99.
- [17] Yu H, Chiang KTK, Yang L. Threshold chloride level and characteristics of reinforcement corrosion initiation in simulated concrete pore solutions. Constr Build Mater 2012;26:723–9.
- [18] Pradhan B, Bhattacharjee B. Corrosion zones of rebar in chloride contaminated concrete through potentiostatic study in concrete powder solution extracts. Corros Sci 2007;49:3935–52.
- [19] Zuquan J, Wei S, Yunsheng Z, Jinyang J, Jianzhong L. Interaction between sulfate and chloride solution attack of concretes with and without fly ash. Cem Concr Res 2007;37:1223–32.

- [20] Al-Amoudi OSB, Maslehuddin M, Abdul-Al YAB. Role of chloride ions on expansion and strength reduction in plain and blended cements in sulfate environments. Constr Build Mater 1995;9:25–33.
- [21] Al-Amoudi OSB, Maslehuddin M. The effect of chloride and sulfate ions on reinforcement corrosion. Cem Concr Res 1993;23:139–46.
- [22] Polder RB. Test methods for onsite measurement of resistivity of concrete a RILEM TC-154 technical recommendation. Constr Build Mater 2001;15:125–31.
- [23] Pradhan B, Bhattacharjee B. Performance evaluation of rebar in chloride contaminated concrete by corrosion rate. Constr Build Mater 2009;23:2346–56.
- [24] Alghamdi SA, Shamsad Ahmad. Service life prediction of RC structures based on correlation between electrochemical and gravimetric reinforcement corrosion rates. Cem Concr Compos 2014;47:64–8.
- [25] IS 383-1970 (Reaffirmed 2002). Specification for coarse and fine aggregates from natural sources for concrete. New Delhi: Bureau of Indian Standards; 2002.
- [26] Neville AM, Brooks JJ. Concrete technology. Delhi: Pearson Education; 2004.
- [27] Law DW, Millard SG, Bungey JH. Linear polarisation resistance measurements using a potentiostatically controlled guard ring. NDT & E Int 2000;33:15–21.
- [28] Gu GP, Beaudoin JJ, Ramachandran VS. Techniques for corrosion investigation in reinforced concrete. In: Ramachandran VS, Beaudoin JJ, editors. Handbook of analytical techniques in concrete science and technology. New Jersey: Noyes Publications; 2001. p. 441–504.
- [29] Erdogdu S, Bremner TW, Kondratova IL. Accelerated testing of plain and epoxy-coated reinforcement in simulated seawater and chloride solutions. Cem Concr Res 2001;31:861–7.
- [30] ASTM C876-09. Standard test method for corrosion potentials of uncoated reinforcing steel in concrete. West Conshohocken (PA): ASTM International; 2009.
- [31] Al-Amoudi OSB. Sulfate attack and reinforcement corrosion in plain and blended cements exposed to sulfate environments. Build Environ 1998;33:53–61.
- [32] Rasheeduzzafar, Al-Amoudi OSB, Abduljauwad SN, Maslehuddin M. Magnesium-sodium sulfate attack in plain and blended cements. J Mater Civ Eng ASCE 1994;6:201–22.
- [33] Hicks CR. Fundamental concepts in the design of experiments. 3rd ed. New York: Holt, Rinehart and Winston; 1982.