Analysis of corrosion performance of rebar in Red mud blended concrete

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Abstract. In this paper, electrochemical technique was employed to evaluate the performance of Red mud (RM) on the reinforcement corrosion. This paper also reports the effect of chloride, sulphate and the combined chloride-sulphate solutions on the corrosivity of rebar embedded in Ordinary Portland Cement (OPC) and RM blended concrete (95% OPC & 5% RM) slab specimens. The corrosion performance was evaluated by Linear polarisation resistance sweep test on the reinforced slab specimens made with mix water contaminated with 5% NaCl, 2% MgSO₄ and the combination of both salts. The corrosion performance was monitored for every 30 days over a period of 180 days, in terms of corrosion rate values. In order to investigate the overall performance of experimental test results they were analysed as per the specifications given by ASTM G16-13. The analysis of the corrosion data includes the descriptive statistics of the Normal, Weibull lognormal, and Smallest Extreme Value probability distribution functions (Pdfs) and the test of fit significance by the Anderson-Darling (AD) goodness of fit statistics. In addition, the analysis of variance was also carried out to determine the influence of each variable on the corrosion data. Further, the analysis of variance is also carried out to evaluate the influence of cementitious material and type of salt on corrosion data.

1. Introduction
Red Mud (RM) is a solid industrial waste obtained from Aluminium industries which is considered as a serious environmental issue due to its alkaline nature (pH ranges from 10.5 to 12.5) and chemical composition. The disposal of RM is also a huge challenge in Aluminium industries due to the need of vast landfills. Throughout the world 120 tons of RM is produced annually. In India, annually significant quantities of RM are stored in areas adjoining the Alumina plants. Due to inappropriate disposal of RM in large quantities, the soil and ground water resources can be contaminated severely. Therefore the utilisation of RM in construction industry needs to be explored to minimize the environmental as well as disposal problems.

From the experimental studies, Belén Díaz et al. [1] explored that the diffusivity values of chlorides and carbon dioxide through RM blended cement paste were significantly reduced. The high Aluminium content of RM able to trap chlorides to produce Friedel’s salt is pointed as responsible for the reduction in chloride diffusivity. On the other hand, the retention in the CO2 penetration is assisted by the larger amount of C-S-H gel developed in the RM-mixtures along with the alkaline nature of the residue. Ribeiro et al. [2] investigated the possible use of RM in corrosion resistance of rebar by monitoring chloride diffusion, corrosion potential and electrical resistivity study. The results showed that the addition of red mud is beneficial to concrete, reducing its diffusion coefficients and corrosion...
potential and increasing its electrical resistivity. Cabeza et al.[3] studied the effectiveness of RM as chloride induced corrosion inhibitor of rebar in mortar specimens and also in the solutions made with red mud and alkaline solutions having the same pH 12. The results show that RM is able to maintain steel passivity in presence of high chloride concentration. Manfroi et al. [4] investigated the pozzolanic property of RM, microstructure and the mineralogy of pastes produced with up to 15% of RM in substitution of OPC. The results have shown that the most appropriate substitution is up to 5% of RM calcined at 600°C.

Several studies have been done on the properties of RM waste and its utilizations for different applications. Nikbin et al. [5] showed that Portland cement can be replaced by as high as 25% of RM. Senff et al.[6] used RM as much as 50% cement replacement in mortar and showed that increasing the RM content decreased the compressive and tensile strengths. As earlier research works suggested the possibility of using RM as the partial replacement of cement for effective corrosion resistance, the present work is aimed to investigate the performance of RM blended concrete in chloride, sulphate and combined chloride-sulphate admixed concrete.

2. Experimental Work

2.1. Materials and specimens

Reinforced concrete slab specimens were prepared with six concrete mixes. The major test variables include cementitious material type and admixed salt type. The plain reinforced concrete specimens were cast with Ordinary Portland cement (OPC) 53 grade conforming to IS: 12269-2013[7] and the blended concrete specimens were prepared with the replacement of cement with Red Mud at 5% by weight of OPC cement. The oxide composition of the cement and blended materials used in the current study were shown in Table 1. The diameter of the steel reinforcing bar was 10 mm. Coarse aggregates of size 20mm and 10mm maximum size of aggregate (MSA) were chosen in the ratio of 1.5:1 respectively as optimum packing. The specific gravity and water absorption of coarse aggregate were 2.8, and 2.25 % respectively, and the corresponding values for fine aggregate were 2.7, and 0.75%. Locally available river sand was used as fine aggregate. Laboratory tap water was used for the preparation of concrete mixtures with w/cm ratio 0.51. Analytical reagent grade chemicals were added to the concretes. The 5% sodium chloride and 2% of magnesium sulphate were added in mix water as the source of chloride and sulphate ions.

Reinforced concrete slab specimens with size 320mm x 320mm x 52mm were prepared with a centrally embedded Thermo Mechanically Treated (TMT) steel reinforcement of diameter 10mm. The steel specimens were cleaned and prepared as per the recommendations of ASTM G109-99a. The reinforcing steel was prepared such that the central portion of length 250 mm remains bare to expose to corrosive environment as shown in Fig. 1.

2.2. Corrosion monitoring

Corrosion monitoring instrument (make: ACM, Gill AC guard serial no. 1824-sequencer) was used to monitor the corrosion performance of rebar in concrete slab specimens. Linear Polarization Resistance (LPR) technique was adopted to determine the corrosion current density values of the concrete slab specimens. This LPR sweep test was conducted with IR compensation, using the guard ring arrangement. The slab specimens were polarized to 20mV from the corrosion potential at a sweep rate of 0.1 mV/second.

3. Results of statistical fitting analyses of corrosion data

Figs.2-4 depicts the $I_{corr}$ values of rebar in OPC and RM blended concrete specimens admixed with NaCl, MgSO$_4$ and NaCl plus MgSO$_4$ respectively. According to ASTM G16-13 [8] statistical evaluation is a necessary step in the analysis of results regarding corrosion performance from any procedure which provides quantitative information. In order to evaluate the overall performance of the variables namely cementitious material type, salt type on corrosion of rebar, the different probability
distribution functions (pdf’s) were adopted. The descriptive statistics for the measured corrosion data were measured using Normal, Lognormal, Weibull and Smallest Extreme Value pdfs as per ASTM G16-13 [8].

Results of statistical analyses of measured corrosion data from each OPC and RM blended concrete specimen contaminated with chlorides, sulphates and combination of both were shown in Fig.5. In order to choose the best fitting distribution, the results of Anderson-Darling (AD) goodness-of-fit (Gof) test [9] of the corrosion test data were also reported in Fig.6. AD p-value with significance level (α) 0.05 is used to choose which distribution fits corrosion data well [9]. A p-value greater than or equal to 0.05 suggests that the modelled distribution significantly drawn from the fitting distribution otherwise not accepted. In Fig. 6 linear plot of significance level (α) 0.05 was included for directly indicating the suitable statistical distribution which fits the corrosion data well. This figure showed that all the $I_{corr}$ data distributed like Weibull pdf while no group of $I_{corr}$ data was distributed like Smallest Extreme Value distribution. It is also observed that Normal distribution is not a good fit for the corrosion data of the plain concrete admixed with chloride and composite solutions as well as the RM blended concretes admixed with sulphates. The p-value less than 0.05 of the lognormal distribution of RM blended concrete admixed with sulphate and composite solutions suggest that the distribution is not a good fit.

Table 1. Chemical composition of cementitious materials.

| Chemical compound | OPC  | RM  |
|-------------------|------|-----|
| $\text{Al}_2\text{O}_3$ | 5.32 | 16.15 |
| $\text{Fe}_2\text{O}_3$ | 4.23 | 54.8 |
| $\text{SiO}_2$ | 20.65 | 6.3 |
| $\text{TiO}_2$ | -- | 3.7 |
| $\text{MgO}$ | 1.13 | -- |
| $\text{CaO}$ | 64.12 | 1.98 |
| $\text{Na}_2\text{O}$ | -- | 3.55 |
| $\text{SO}_3$ | 2.16 | -- |
| Others | -- | 1.72 |
| LOI | 2.39 | 11.8 |
| Specific gravity | 3.13 | 3.1 |

From the Fig.6, it is observed that the P-Value for Weibull distribution of all concrete specimens with different admixed solutions was more than the significant value 0.05, which means that all the corrosion current density values were drawn from the Weibull distribution. The overall performance of OPC and RM blended concrete specimens was evaluated from the use of this selected Weibull distribution as shown in Fig.7. These identifications of descriptive statistics for detailing the corrosion data highlights the importance of the use of goodness-of-fit test for determining the probabilistic distribution fitting followed by the corrosion data.

4. Analysis of Variance

Analysis of Variance (ANOVA) was carried out for the experimental $I_{corr}$ data as the response and the two levels (OPC, RM) of cementitious material type and three (Chloride, sulphate and combination of both the salts) levels of salt type as discrete variables. The ANOVA was adopted to determine the statistical significant difference between the type of cementitious material and slat type.
Figure 2. Experimental test results of NaCl admixed concrete

Figure 3. Experimental test results of MgSO₄ admixed concrete

Figure 4. Experimental test results of NaCl plus MgSO₄ admixed concrete

Figure 5. Analysed results of $I_{corr}$ data of OPC and RM concretes admixed with chloride, sulphate and composite solutions.

The obtained $I_{corr}$ values at various levels of cementitious material type (CM), salt type are arranged in tabular form. After that the sum of the squares (SS) for factor and residual error were calculated. Then the mean square (MS) of the factor is calculated by dividing their corresponding sum of squares by associated degree of freedom (DF). Then the effect of individual factors is evaluated by testing the hypothesis of equality of variances. In analysis of variance the most important statistics is the P-value, which used to determine whether the level of means are significantly different from each other about the hypothesis with 95\% confident level ($\alpha=0.05$). The hypothesis for the present study is given below[10]:

- P value $\leq 0.05$: The level means are significantly different from each other
- P value $> 0.05$: The level means are not significantly different.

While observing the effect of salt type on corrosion of rebar from the Fig.6, it is observed that the corrosion due to sulphate ions is very less as compared to chlorides. As well as it is also observed that the presence of sulphate ions with chlorides enhances the chloride induced corrosion in OPC concrete but not in RM blended concrete. The replacement of cement with 5\% of RM enhanced the corrosion resistance of rebar in concretes contaminated with chlorides, sulphates and combination of both the salts.
5. Conclusions
From the present experimental study the following conclusions are drawn:
1. The incorporation of 5% RM in concrete is beneficial to enhance the corrosion resistance of rebar embedded in concrete.
2. The corrosion due to sulphates is negligible as compared to chloride induced corrosion in both plain and RM blended concrete.
3. The presence of sulphates enhances the chloride induced corrosion in normal OPC concrete but the opposite trend was observed in RM blended concrete.

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