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Electrochemical Protection of Steel in Concrete

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Abstract:-Corrosion of buildings made of reinforced concrete is a big issue all over the world, necessitating large sums of money for repair and restoration. This study is concerned with the finding of the optimum choice of the electrochemical chloride Removal (ECR) current and its duration of application. For 1 to 4 weeks, three consistent ECR current density levels of 100, 200, and 300 A/cm2 were pulsed to a reinforced concrete specimen of dimensions 150mm x 150mm x 300mm containing 0%, 1%, 2%, and 3%. In order to ensure the progress of the applied procedure, the left-out chloride content around the reinforcement was examined. To investigate the corrosion status following ECR, open circuit potential, and corrosion rate observations were taken. Additionally, the pH around the reinforcement and resistance of concrete to electrical conductance was measured. The ideal current density and duration were determined based on the above test findings. To test the efficiency of the ECR process, a 1m x 1m x.1m slab is taken for further experimental examination employing electrochemical investigations like Tafel, AC Impedance, and LPR measurement.

Keywords*: Electrochemical chloride removal (ECR) current, ECR duration, Open circuit potential, corrosion rate, pH, Chloride concentration, Titanium anode.*

1. Introduction

Corrosion of Steel in concrete is a serious hazard to the construction sector. The primary contributory factor of reinforcement corrosion is chloride ingress. Several protection methods are used to prevent corrosion, such as covering concrete, coating rebar, adding inhibitors, employing supplemental cementation ingredients, and electrochemical steel protection, among others. The electrochemical protection method is one of the most emerging and promising methods of protecting against corrosion of rebar both in existing and to-be-constructed structures. In this research work, optimization is done for electrochemical chloride removal (ECR) current and the ECR duration. Also, the current work deals with the proper selection among the three constant ECR current densities namely 100, 200, and 300 µA/cm2, which will be applied to reinforced concrete beams of size 150mm x 150mm x 300mm. Four slabs were tested. They contain 0%, 1%, 2%, and 3% of chloride. The duration is considered as 1 to 4 weeks.

In this work, an existing structure (a slab of size 1m x 1m x .1m) was selected. The chosen ECR process (density & duration) is done on this existing slab & a fresh slab with pickled reinforcements. The embedded steel's potential and the current flowing between the anode (Titanium) and the steel are monitored, mapped out, and evaluated. The chloride content of concrete at various sites at various times was also measured and studied. Electrochemical studies (Tafel, AC Impedance, LPR measurement) were done on the slab to measure the efficiency of the ECR technique.

Since the steel is embedded inside the concrete in reinforced concrete it protects the rod inside it both physically and chemically. Due to this, reinforced concrete performs superior in terms of structural performance and durability. oxide/hydroxide coating can be generated over the steel surface by means of the high alkalinity (pH=13-14) of concrete pore solution. This formulation effectively retards the steel from electrolytes and reducing the corrosion rate. Corrosion of embedded rebar inside the concrete stimulated due to the presence of chloride is the most important and common cause of early degradation of reinforced concrete across the world.

Structures like highway bridges exposed to de-icing salt and those exposed to coastal or marine exposure are highly prone to this kind of chloride-induced corrosion. Since the process of removing chloride-containing material significantly from each component of the structure is very tedious, the well-known patch repair method will not work for a long-term solution. Even if it is applied the method will obviously be an un- economical solution as it requires intensive treatment and also temporary support.

Hence it is mandatory to develop an alternate preventive solution to overcome the problems created by corrosion due to the presence of chlorides. In order to treat chloride stimulated corrosion a promising method was established namely Electrochemical chloride removal (ECR). IN this method a high DC current density is passed via the cover concrete. Here the reinforcing steel is kept as cathode and an external probe act as anode in the structure. The core concept of this method is to eliminate a possible maximum amount of chloride from the concrete. The procedure used here is electromigration. Another aim is also to complete the procedure in a short period of time. This is one of the most advanced and current age technique for preventing chloride- induced corrosion of reinforced concrete. The main criteria which affect the efficacy is electrostatic charge produced in the pore solution. This induced charge must be able to counteract the moving force of chloride ion concentration in the concrete area.

A. Pérez et al. [3] utilised a conductive cement paste as anode to meet up the efficiency of classic Ti–RuO2 anode. He showed how effectively chlorides can be extracted from reinforced concrete by means of electrochemical process. He utilised a combination of one third portion of cement cement (the same cement used in the concretes), one third portion of graphite powder, and one third portion of distilled water for the conductive cement paste that is to be used as the anode. He stated that, the acidity created by the reaction induced by anode might cause some harm to a CCP anodic overlay during treatment. However, it does not result in an anodic system dysfunction. Takao Ueda et al. [2] To improvise the mechanical properties and lifetime he tested a ductile fiber-reinforced cementitious composite as a new anode system.

G. Fajardo et al. [4] tested some cylindrical concrete specimens in the laboratory, by introducing it into a "fake" sea water as a source of chloride. He demonstrated that after some time the efficacy of ECE gets reduced. Cover depth greatly affects the time required. J.C. Orellana et al. [7] investigated about the resistance offered by aggregate to alkalinity when it is immersed in NaCl solution. Even though this method decreases the chloride level by 40-45%, there is evidence of presence of alkali ions encompassing the steel. P. Garcés et al. [5] investigated the efficacy of the electrochemical chloride removal (ECR) for varied bar layouts. He concluded that the chloride extraction can be improved by means of providing a uniform layer configuration. R.N. Swamy et al. [6] studied the efficacy and structural consequences when the ECR process is applied on RC beams that contain chloride and also beams containing a combination of chlorides and reactive aggregates. He also found that when the beam contains reactive particles the amount of chloride reduction increased marginally.

2. Experimental Investigation

2.1 Material Property

We used a cement of Type I, sand with a fineness modulus of 3.01, and coarse aggregates sourced locally. The deformed rebar utilized in this project has a Modulus elasticity of 203 GPa and strength against a yield of 410 MPa. The electrolyte utilized was a pore solution (0.1N NaOH+0.3N KOH+0.03N CaO). A mesh made of titanium is used as an anode that is having an electrical resistivity of $5.6\times10-5\ \Omega$ cm. For specimens that are contaminated given the dosages of 1%, 2%, and 3% NaCl dosages by weight of cement.

2.2 Ization Of Ecr Parameters

The main two aspects which are to be designed in this project are ECR current density and the duration for which the ECR is to be applied. There are two approaches through which an electric field can be applied to the rebar inside the concrete. One is electric field density and current density both are applied at a constant rate. In this investigation, the current density was applied at a constant rate. ECR was designed with three constant current densities: 100, 200, and 300 A/cm2. Here the area for which the above-mentioned density is considered is nothing but the protected area of the rebar. The duration was fixed as from one to four weeks.

2.3 Experimental Methods

The main aim is to design the ECR process for a slab made of reinforced concrete. Before finalizing the parameters, concrete beams were tested for the result. Here the cover thickness is considered as the distance between the bottom of the beam to its nearest reinforcement. Here it is kept at 2.5cm. The dimension of the concrete beam is 15 cm×15 cm×30 cm. The reinforcement skeleton of the beam specimen is shown in figure 1.

Figure 1a– Beam **Figure** 1b - Slab

Figure 1- Reinforcement skeleton of Beam and slab

Figure 2- Reinforced Concrete Beam

The beam specimens casted were shown in figure 2. The slab specimens with various chloride ion exposure were shown in figure 3. Two numbers of slab were casted namely for 0% chloride and 3% chloride exposure. The casted specimen is kept for 28 day curing period. Followed by curing the specimens were supplied with DC power to initiate the required ECR process. The ECR electrolyte was the pore solution containing 0.1N NaoH, 0.3N KOH, and 0.03N CaO, and based on the results obtained through chemical titration, the concentration is adjusted on a daily basis. Since the ECR current density is to be monitored or maintained, an adjustable resistor was utilised.

Figure 3a – RC slab with 0% **Figure 3b– RC slab with 3% cl2**

The concrete specimens were separated from the ECR equipment once the designed ECR duration is destinated. After completing the ECR application process number of trials were carried out as mentioned here. The concrete that is surrounding the reinforcements were plucked off. Approximately 3cm is scaled as extraction zone so that the sample height will be of 1cm in the direction of cover thickness. The pH value and residual chloride ion concentration is determined through laboratory experiments. The standard ECR idea is to remove the free chloride ions on the whole from the concrete. Despite the formal procedure here a concept of pushing- away of chloride ions from rebar to desired length is employed. This method of pushing-away maintains a balance between corrosion protection and degradation of bond. The core idea of project is to drive away the free chloride ions from the rebar inside the concrete to some distance where corrosion will not occur for a reasonable time. This time mainly depends on the distance to which it is been pushed and the rate of diffusivity of the pushed chloride ions. The front-line goal of this study is to design the ECR parameters for the prevention of rebars from corrosion. The parameters are scaled based on two indicators namely pH value and chloride ion concentration.

2.3.1 Open Circuit Potential Test

A voltmeter with a high input impedance of 20 mega ohms is utilised for measuring half-cell potential of rebar at a regular basis. The rebar is nothing but placed inside the concrete. The voltmeter's positive terminal was attached to the steel, while the negative terminal was linked to the saturated calomel electrode. (SCE). The potential of steel was also measured against the stainless-steel electrode. The pore solution is kept as an electrolyte for the setup. Till the end of designated period the potential of the rebar of all the beam specimens were monitored. All the potentials are monitored concerning saturated calomel electrodes (SCE) and stainless steel electrodes at a room temperature of 35±1oC. From the OCP measurements, the potential-time behaviour was measured.

Figure 4– Open Circuit Potential test set-up

2.3.2 Chloride Content Estimation (free chloride)

Using the standard method of titration, the electrolyte was tested periodically for how much chloride was moved into it. 5 ml of the test solution is taken into the conical flask. After that two drops of phenolphthalein indicator are added into the solution. The solution turns to pink color. It means that the solution is more alkaline. When it is neutralized by 0.1N sulphuric acid it attains colorless. Then a few drops of potassium chromate is added as an indicator. Then it is titrated against 0.01N AgNO3, the endpoint is the appearance of red color. This experiment is repeated to get a concordant value.

Free chloride (ppm) = (Titre value x 35.43 x 1000 x Strength of AgNO3) / Amount of solution taken.

3. Results and Discussion

3.1 Open Circuit Potential

3.1.1 OCP of 1A/m2 Specimen (Current ON condition)

The results obtained in the Open Circuit potential against Standard Calomel and Stainless-steel electrodes were plotted in the graph below.

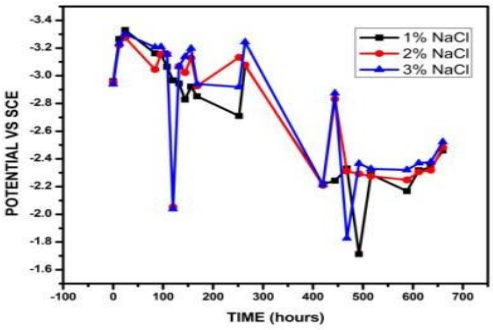

Figure 5 -Potential vs SCE for various percentages of chlorine.

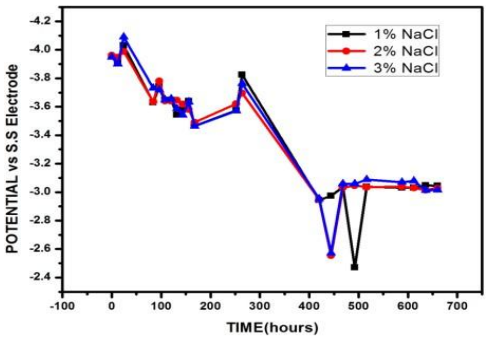

Figure 6- Potential Vs S.S.E for various percentages of chlorine.

3.1.2 OCP of 1A/m2 Specimen (Current OFF condition)

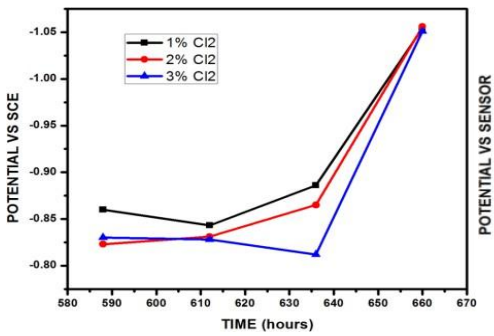

Figure 7- Potential vs SCE for various percentages of chlorine.

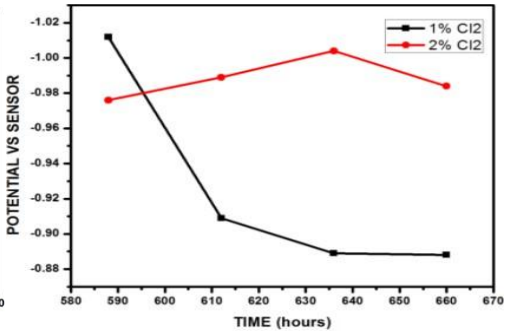

Figure 8-Potential vs MnO2 for various percentages of chlorine.

From the above graphs, it is clear that the potential got shifted towards less negative as the current is applied continuously for 1 week and slowly got stabilized. After a rest period of 3 days, the current density is applied again to get higher efficiency. As said, in the second phase of the current application the potential shift is higher than that in the first phase. It is also seen from the graph that the potential got stabilized at 660 hrs (around 4 weeks).

3.1.3 OCP of 3A/m2 Specimen (Current ON condition)

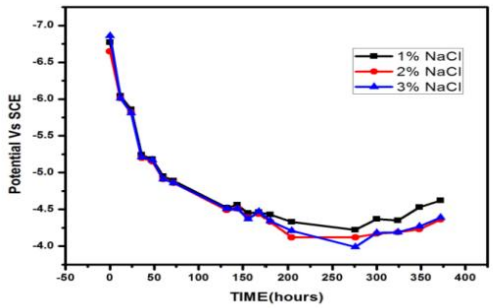

Figure 9 - Potential vs SCE for various percentages of chlorine.

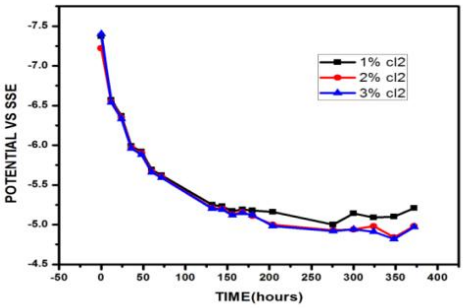

Figure 10- Potential Vs S.S. Electrode for various percentages of

3.1.4 OCP of 3A/m2 Specimen (Current OFF condition)

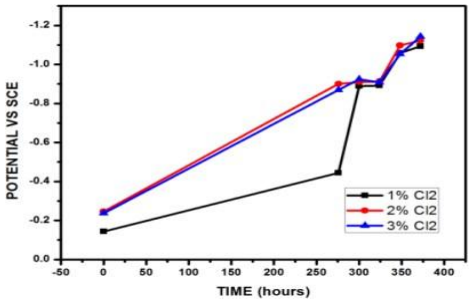

Figure 11-Potential vs SCE for various percentages of chlorine.

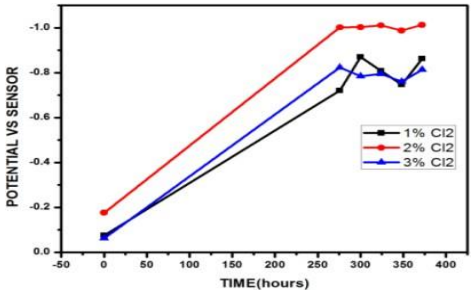

Figure 12- Potential vs MnO2 for various percentages of chlorine.

From the above graphs, it is observed that the potential got shifted rapidly towards less negative than that in the 1A/m2 specimens. It is also to be noted that the potential got stabilized in 348 hrs (around 2 weeks). At this stage, the current application can be stopped and can be applied after a sufficient duration.

3.2 Chloride Content

3.2.1 Chloride Content of 1A/m2 specimen

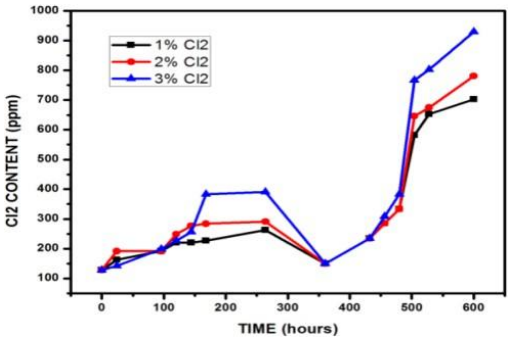

Figure 13- Chloride removal for various percentages of chlorine

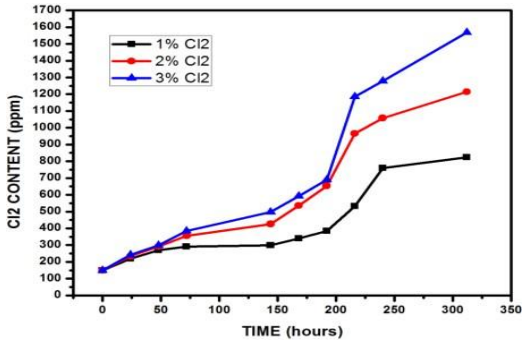

Figure 14- Chloride removal for various percentages of chlorine

3.2.2 Chloride Content of 3A/m2 specimen

From the figure it is observed that the amount of chloride removal in 3% chloride-contaminated concrete is found to be 23,515 mg/l while applying a current density of 3A/m2. The chloride clearance rate in 3% chloride-contaminated concrete was found to be double that of 1% chloride-contaminated concrete. It shows the increase in the amount of free chlorine present in 3% chloride-contaminated concrete.

Table 1- Chloride Removal for 1A/m2 current application

Chloride %	Initial amount (ppm)	Removal after 1 week (ppm)	Removal after 2 weeks (ppm)	Removal after 3 weeks (ppm)
1	13800	3940	4275	10530
2	27600	4366	5296	11715
3	41400	5858	6420	13950

Table 2- Chloride Removal for 3A/m2 current application

Chloride %	Initial amount (ppm)	Removal after 1 week(ppm)	Removal after 2 weeks(ppm)
1	13800	5107	12360
2	27600	8025	18210
3	41400	8895	23535

4. Conclusion

From this study, optimum current density and duration were standardized in small-scale studies and the same can be implemented for field applications. It is found that concrete with 3% chloride contaminated specimen subjected to 3A/m2 of current density was found to remove 43% of free chloride present in the concrete. The optimum ECR duration was found to be 2 weeks and the optimum ECR current density was observed to be $3A/m^2$.

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