An experimental study on assessing the corrosion performance of steel reinforcement for the durability of concrete

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Abstract. Durability of structures made of steel-reinforced concrete is greatly to scale back the speed of moisture transport or the ingress of aggressive ions. An experimental study to assess the initial corrosion behaviour of Thermo-Mechanically Treated rebar (TMT), Corrosion Resistant rebar (CRS) and Fusion bonded Epoxy Coated rebar (EC) under controlled condition (CC) and in simulated marine environment condition (SME). Rebars of 12 mm dia with a span of 250 mm are enclosed in specimens having a length and breadth of 350 mm and a thickness of 138 mm then initial study was carried out. The corrosion potential is noted throughout the specified duration and once in three days of observing the corrosion potential gives the likelihood of corrosion rise. The A.C Impedance and Polarization resistance methods are used to study the corrosion rate in the surface of the rebar. The polarisation resistance ($R_p$) of TMT rebar is found to be 1.8 times but that of CRS rebar. A.C Impedance used for EC showed that epoxy coating is harmed and affected because of chloride attack. Initial quantitative study from this research gives clear interpretation of rust production which can be utilized in fragility of the structure.

1. Introduction

Early negligence of reinforced concrete assembly happens fundamentally because of premature corrosion of rebar. The two most persistant action occurring foremost in rebar corrosion are effervescence of concrete and chloride intrusion which supply an extremely decaying environment for the implanted steel. The corrosion by-product so found are further more generous besides the rear constituents. The progress of corrosion in reinforcing steel, expands and occupies a volume of about 6–10 times greater than that of steel which results in the formation of cracks leads to failure of structures. As, when prevailing corrosion rate quantification methods are practical for speedy monitoring of structures, which enhance fairly high cost and if inappropriate examining is carried out over prolonged duration. The corrosion of rebar in concrete is a significant issue from the outlook of protection and economic restraint which influences the feasibility of the framework configuration.

It is noticed that constituents of reinforcement bar plays a remarkable role in critical chloride effectiveness that commences the decay of rebar. The amount of chloride ions need to commence the decay of rebar in concrete matches with 0.10% dissolved chloride ion on cement weight [1,2] some corrosion resisting agents influences the protective film on the enclosed rebar which commences the decay of rebar in place effervescence starts which eventually decreases the decay of rebar. This
phenomenon can be prevented by a number of techniques by providing sufficient cover to concrete, use of migratory corrosion inhibitors such as calcium nitrate, sodium nitrate, sodium monofluorophosphate etc, using concrete sealers as silane sprays, acrylic sealers and linked oil emulsions and by adding silica fume to concrete which shows carbonation and keeps chlorides out which reduces rebar corrosion and it is obviously detected that addition of silica fume uncertainly imparts to lower the porosity of concrete to chloride ions [3]. Daoming Shen suggested that steel becomes inactive when chloride to nitrite ratio should not be equal to greater than 1 [4-6]. It is established that decay of rebar on the anode area mostly rely on the oxygen supply and chloride content and results showed that proliferation under macro cell corrosion is due to the consequence of w/c ratio, cover depth etc [7]. Vedaralakshmi et al suggested that decay of rebar in PPC and PSC had more decaying resistance in 30 MPa concrete [24]. In the vigorous corrosion condition, the high chromium steel normalized beneath ASTM A1035/A1035M-16b having a mild carbon content of 0.1% and chromium content of 9-11% [9] provided to have 1.5-2 times higher confrontation to charge transfer in vital condition to corrosion. The durability of RC structures in zones were moisture and chloride mass are excessive like marine environment, the utilization of EC and HC is anticipated [25]. An imperfection less overlay is extremely impenetrable to the dispersing of chloride and other ions. Condensation yet, infiltrates past coating but the amount of corrosion rate irritates only when chloride ions are nearer to the junction of covering [11] and visual inspection reveals that no decay of rebar was found below galvanized coating when pH is greater than 13.3 and found more active to rear a long time shielding [12-14] were the epoxy/galvanized binary cover over the rebar possibly flatters a capital approach in corrosive habitat construction [15]. Erdogdu et al. concluded that EC when subjected to couple of years under chloride habitat, 1% and 2% impairment experiences minor decay of rebar and no severe symptoms of corrosion is detected [16]. Interpenetrating Polymer Network-coated reinforcement possess sustainable firmness, more extended life on concrete which experiences greater corrosion resistivity [17]. Venkatesan et al. concluded that at different environmental conditions CPCC coated rebar performed well when tests conducted at atmospheric level, high tide level and at sea floor level [18]. Song et al. studied that by mixing of PPC+PSC along with 0.3% NaCl and with 0.2% of alkaline nitrates showed that the emergence of this kind intricate much lower permeability and decay of rebar [19], the corrosion rate of the reinforcement steel is inversely proportional to the polarization resistance [20] were existing A.C Impedance is a well-founded technique to evaluate the corrosion rate of rebar beneath epoxy coating steel which showed that R_p for TMT, HC is lower than that of EC [25].

In the following study, three types of concrete reinforcements, Thermo-Mechanically Treated Bars (TMT), High Chromium Steel Bars (CRS) and Fusion Bonded Epoxy Coated Reinforcements (FBECR) are implanted in the concrete specimens and corresponding corrosion rates are monitored in a confined environment as well as in environment supposed to high salinity by sprinkling the surface with 3% of NaCl solution. Then the specimens are subjected to Electrochemical Techniques, for corrosion monitoring by Open-Circuit Potential (OCP), Linear Polarisation Resistance (LPR), A.C Impedance. and by Gravimetric loss of the reinforcement, however the A.C Impedance which demonstrates to be the utmost acceptable application to monitor the corrosion effect of EC, were the corrosion of elemental steel (Iron), was utilized.

2. Experimental program
2.1. Materials and Mix proportions
The considered Bare TMT, CRS and Epoxy Coated confirming to A615/A615M – 18 [8], A1035/A1035M – 16[9], A775/A775M – 19 [10] respectively. Incipient weight of rebar is deliberated with the help of physical balance having a sensitivity of 0.01g which when done after treating the rebar with pickling solutions. Concrete specimens were casted for a mix proportion having a characteristic compressive strength of 30MPa after 28 days of curing. Ingredients of mix proportion are given in Table 1. Type I Portland Pozzolana Cement of 53 grade confirming to IS 1489(Part I):1991, Coarse aggregates with maximum sizes of 16mm and 12mm are used in fractions of 60%,
40% with a fineness modulus of 5.62 and Fine aggregates passing through 4.75mm sieves having a fineness modulus of 4.82, both confirming to IS 383:2016 is used for concrete specimens. The grading of coarse and fine aggregate are shown in figure1. Potable water was used for casting the concrete.

Table 1. Details of concrete mix proportions.

| Concrete Grade | w/c Ratio | Cement (kg/m³) | Water (kg/m³) | Fine Aggregate (kg/m³) | Coarse Aggregate (kg/m³) |
|----------------|-----------|----------------|---------------|------------------------|-------------------------|
| M30            | 0.5       | 340            | 180.2         | 687                    | 1185                    |

Figure 1. Grading of coarse and fine aggregate.

2.2 Sample configuration
Twenty-four concrete slabs with dimensions of 350mm×350mm×138mm were cast. Reinforcement bars of 12 mm diameter were cut at 250mm length and 50mm length, is implanted in centre of concrete slabs. Cover concrete thickness of 50 mm was provided from the top of each specimen. Sample of three numbers in each type of rebar is casted to make sure the fickleness in ingredient effects and evaluating methods is ensured properly. Specimens casted is identified by means of punching number, i.e., TMT, Corrosion Resistant Steel and Epoxy coated steel followed by a number from 1 to 3, e.g., first TMT specimen is identified as 1, and along with others. To setup the interdependence for electrochemical measurements a copper wire is affixed. To setup electrical connection in EC rebar, a 2mm wide open of epoxy is eradicated in the circumference for suppressing moisture entry and chloride admittance M-Seal is pertained over the rebar surface. The rectangular configuration permits constant dissolution on rebar by exterminating the mistakes and in assessing of polarised steel area throughout the electrochemical study. Rebar is perfectly implanted in specimens to ignore the effect of surroundings which causes corrosion. In advance of implanting the rebar, the oxidised lamina is detached from all the rebar by scouring the surface with dil. Sulphuric acid and then allowed to dry. After measuring the incipient weight, electrical leads made of copper is winded on top
of rebar which enables the rebar perfectly implanted in the concrete specimen and only the electrical leads is unveiled externally through which electrochemical measurements are done. Equivalent slab samples are casted. The specimens are cured for 28 days after demoulding.

![Concrete test slab for corrosion monitoring.](image)

**Figure 2.** Concrete test slab for corrosion monitoring.

2.3 Method of Exposure

2.3.1 Controlled Environment Exposure

The slab samples are influenced to normal environment condition, having a humidity of 27±2°C. The surface of the specimens are wetted with potable water atleast 1 hour prior to the observations taken, so that the passivity if the steel is removed considerably with the variation in time. Observations are taken once in three days for the specimens and the loss in passivity of the specimens are observed.

2.3.2 Simulated Marine Environment Exposure

The specimens were subjected to alternate wetting and drying in 3% NaCl solution. The NaCl solution was sprayed over the surface of the specimens at an interval of eight hours, and the readings are observed once in three days. Throughout the elucidation of salt infusion, chloride ions tends to spread past the concrete cover and motivates the rebar to corrode.

3. Testing methods

3.1 Open Circuit Potential (OCP) measurement

The steel reinforcement implanted in the specimen is observed periodically in case of saturated calomel electrode (SCE) as reference. OCP measurements were made using a multimeter, were the positive terminal was connected to the reference electrode and three readings are taken very close to the rebar and the variation should not be more than ±10 mV. OCP estimates only the probability of corrosion and it does not specify the corrosion rate. ASTM C876 relates the OCP to the likelihood of the rebar corrosion in concrete specimens. Table 2 relates the diversity correlated with lowest relevancy to extreme corrosion risk.
3.2 Linear Polarization Resistance (LPR) technique
Linear polarisation resistance measurements are taken at regular intervals once corrosion initiation was determined based on OCP values. LPR quantification is directed with the help of ACM field machine (UK). The probe has a three electrode fabrication were rebar implanted in concrete which functions as working electrode (WE), a reference electrode (RE) is the saturated calomel electrode is used and a stainless steel plate which acts as a counter electrode (CE) were used. During testing the samples are properly wetted with potable water, this was to make sure the accessibility of oxygen in the junction of steel and concrete.

LPR in this study is obtained, when the rebar is polarized in the potable scale of ±20 mV from OCP with a sweeping frequency of 0.2mV/s is applied on the steel rebar and the current retaliation is recorded. The polarisation resistance $R_p$, from the rebar implanted in concrete is acquired from the slope of potential curve. With the help of the following relationship (1) in the corrosion current $I_{corr}$ ($\mu$A/cm$^2$) and rate of corrosion is acquired.

$$I_{corr} = \frac{B}{R_p}$$

where B is the Stern-Geary constant = 52 mV

3.3 Electrochemical Impedance Spectroscopy (EIS) technique
The guideline of this method is to put in an interchanging indicator of lower extent (5-20 mV) to the electrode (rebar) implanted in the electrolyte (concrete). The EIS works in the frequency domain.
(resistance, capacitance and inductance), in which impedance, \(Z = \frac{\Delta E}{\Delta t}\), is measured using Ohm’s law by applying the selected sine curve, \(V(t) = V_0 \sin(\omega t)\) at a stipulated sweep of recurrence, \(f = \frac{\omega}{2\pi}\) is related to the rebar and the transient response, \(I(t) = I_0 \sin(\omega t + \theta)\), which has a phase shift of \(\theta\) from the applicable electric potential difference is observed.

![Nyquist plot and equivalent circuit](image)

**Figure 4.** Corrosion process in RC by Nyquist plot and its equivalent circuit.

In the present study, the EIS sweep is conferred by Nyquist plot, showing the electrical resistance in argand plane of cartesian co-ordinates, i.e., \(Z = Z' + jZ''\), where \(Z'\) and \(jZ''\) show the existent and non-existent segments strained on the polar co-ordinates and abscissa of the graph appropriately. Further description called as Bode diagram, showing the approximation of the electrical resistance modulus and phase shift as a sweep of recurrence approximation. Depending upon the configuration of corrosion process in concrete, the illustrative of classic Nyquist plot for the EIS sweep in reinforced concrete is given in fig. 4. To acquire the EIS sweep, an electric potential difference of 10 mV is pertained with a sweep of recurrence of 0.1 Hz to 30kHz. Electrochemical Impedance spectroscopy is examined as a practical non-corrosive method for measuring the corrosion of reinforcement implanted in concrete. This method is extremely appealing since, worn in an extensive sweep of recurrence which gives elaborate details regarding the appliance energy of electrochemical responses.

### 4. Results and discussion

#### 4.1 Open Circuit Potential

The OCP of TMT, CRS and EC under controlled condition (CC) and simulated marine environment condition (SME). OCP decreased during the first few days before the concrete sample becoming stable in case of both CC and SME, then later on dripped to increase the electronegative values. In the LPR study, the OCP sample for both CC and SME varied from \(-193\text{mV/SCE}\) to \(-224.31\text{mV/SCE}\) for TMT, from \(-164.23\text{mV/SCE}\) to \(-213.68\text{mV/SCE}\) for CRS and from \(-345.07\text{mV/SCE}\) to \(-415.42\text{mV/SCE}\) for EC. The pattern of corrosion potential for CC is influencing lesser corrosion susceptibility when compared with SME as per fig. 5 (a) and (b). The sensitivity of corrosion on rebar is assumed from OCP values in the succeeding manner from high level to low-level: EC, TMT and CRS.

The standard drip in OCP estimates from non-resistant to resistant state is less in case of CRS rebar among the three types of rebar used. This is in fact shows that samples under SME have the ability to undergo an excessive level of corrosion rate after termination of investigation. The effect of perviousness due to corrosion sensitivity of concrete samples under CC and SME is explained in former segments.
Figure 5. OCP in Controlled and Simulated Marine Environment Condition.

4.2 Linear Polarization Resistance
The LPR curves shown in the fig. 6 shows an apparently lined behaviour in the complete dissolution sweep; were, a divergent reaction of -20 mV dissolution is given at the start of the experiment for all the three types of rebar embedded specimens. In case of LPR study, the unique line distribute of the curve is analysed to find the dissolution resistance $R_p$. For LPR study, a 5 mV to 20 mV dissolution is endorsed and the lined distribute in this range can be analysed to acquire the dissolution resistance.

Since the sweeping frequency commences at 0.2 mV/sec, there can be a little variation of current connecting the stainless steel plate which acts as counter electrode and water around this voltage acts as a capacitor. The average values of $R_p$ over three specimens be 92.2 kΩ.cm$^2$, 33.76 kΩ.cm$^2$ and 20.9 kΩ.cm$^2$ for TMT, CRS and EC accordingly, during the initiation of the study.

Figure 6. Linear Polarization Resistance curves for TMT, CRS and EC.
4.3 Electrochemical Impedance Spectroscopy

The Nyquist plots of the studied rebar in fig.7 shows the initial corrosion study. The TMT and CRS rebar showed a similar behaviour, in case of EC it showed a bit dissimilar Nyquist plot formation when compared with coating free rebar at greater sweep of recurrences. The complete resistance accounts for charge transfer resistance \( R_{ct} \) and concrete resistance \( R_c \). Generally, the concrete and the steel-concrete junction are impure condensors, in which these condenser curve as an alternative existence of an ideal half circle found over the existent axis (as shown in fig. 7), they are impaired with centres beneath the existent axis.

An unresisting steel below the EC showed a greater charge transfer resistance than TMT and CRS. The standard parameters of the electrical resistance limit acquired by connecting the plot is shown in Table 3. The concrete resistance \( R_c \) was acquired to be within 22.9 kΩ.cm², and 38.5 kΩ.cm², while the capacitance of bulk concrete was between \( 10^{-4} \) mA/cm² and \( 10^{-6} \) mA/cm². The charge transfer resistance \( R_{ct} \) was observed to be 105 kΩ.cm², 17 kΩ.cm², and 46 kΩ.cm² for EC, CRS and TMT accordingly. The higher steel resistance designates that the inner curve acquired from Nyquist plot emerged from the surface of the electrode. However, the LPR and EIS methods recommend that \( R_p \) values exists in similar manner from (fig.7), the EIS method shown a bit less \( R_p \) for coating free rebar. Considering the EIS method which applies alternating current (AC) which passes pass the epoxy coating is declared that the entire span of EC is dissolved; then the range of electrochemical impedance sweep is in allowable reach as the rebar in corrosion offers a lower dissolution resistance under CC and SME.

![Figure 7. Electrochemical Impedance Spectroscopy curves for TMT, CRS and EC.](image-url)
Table 3. Average values of LPR and EIS parameters.

| Type of Rebar | $R_c$ (kΩ.cm$^2$) | $R_{ct}$ (kΩ.cm$^2$) | $C_{dl}$ F/cm$^2$ | $I_{corr}$ mA/cm$^2$ | Corrosion rate (mm/year) |
|---------------|-------------------|----------------------|-----------------|---------------------|------------------------|
| TMT           | 22.9              | 46                   | 1.36×10^{-4}    | 5.64×10^{-4}       | 6.53×10^{-3}          |
| CRS           | 26                | 17                   | 3.43×10^{-5}    | 1.54×10^{-3}       | 1.78×10^{-2}          |
| EC            | 38.5              | 105                  | 3.51×10^{-7}    | 2.48×10^{-5}       | 2.88×10^{-4}          |

Figure 8. Charge transfer resistance and Polarization resistance calculated by LPR and EIS.

5. Conclusions

In the modern development of infrastructures, stability and resilience is given the utmost importance, this consideration is essential in assessing and resembling the effect of corrosion in concrete. Corrosion study have become a requirement of periodic life support as insistent circumstances arise in concrete because of chloride ingress or by carbonation. The resilience effect on three types of rebar embedded in concrete with reference to defiance of corrosion in controlled as well as in simulated marine environment condition was evaluated for the initial study. The specimens in CC subjected to a room temperature of 27±2°C and in case of SME the specimens are sprayed with 3% NaCl over the surfaces at an interval of eight hours.

The OCP values suggested the probability of corrosion of the steel rebar during the study. During the study, the OCP values under CC and SME were in the range of -193 mV/SCE to -224.31 mV/SCE for TMT, from -164.23 mV/SCE to -213.68 mV for CRS and from -345.07mV/SCE to -415.42 mV/SCE for EC. These values are observed in the initial condition of the study were more electronegativity will be observed in later durations.

The dissolution defiance of rebar is acquired by LPR and EIS. The polarization resistance measured from LPR were 92.2 kΩ.cm$^2$ and 33.76 kΩ.cm$^2$ and for TMT and CRS appropriately which shows the more resistance than EIS. In case of EIS study for EC, it showed more resistance when compared to LPR i.e., 105 kΩ.cm$^2$ by EIS and 20.9 kΩ.cm$^2$ by LPR; which shows that for uncoated rebar LPR will be more useful and EIS is utilized to monitor the well-being of epoxy and to monitor the corrosion of
steel below epoxy coating. The benefit of EC is anticipated to increase the durability of RC structures, particularly when periodic decay is extended in the regions where chloride accumulation is heavy and at that point deterioration of RC structures will become a considerable fit out.

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