Effect of IR Drop on Reinforced Concrete Corrosion Measurements

U.Raghu Babu¹,a, B.Kondraivendhan²,b

¹,² Civil Engineering Department, Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India

a ammaraghubabu@gmail.com, b kondraivendhan78@gmail.com.

Abstract. The ohmic voltage drop (IR) due to the high resistivity of concrete needs to be considered while monitoring the corrosion performance of rebar embedded in concrete. It helps to evaluate the corrosion condition precisely. Concrete mixes were contaminated with chlorides, sulphates, and a combination of chloride plus sulphate solutions as mix water. To assess the IR drop error in corrosion measurements caused by concrete with different salts, linear polarization resistance values were measured with and without IR compensation. The results indicate that the concrete contaminated with 5% of chloride has shown higher error as compared to 2% of sulphates, due to high corrosion current density. However, from the results of chloride and chloride plus sulphate contaminated concrete, it is also confirmed that the IR drop error is not absolute to determine the solution resistance. The higher corrosion in chloride contaminated concrete as compared to chloride plus sulphate contaminated concrete is also observed due to the availability of high chloride concentration. The results of the present study are suggested that the IR drop compensation should be considered when the reinforced structures are exposed to chloride and sulphate environment.

1. Introduction

Reinforcing steel embedded in concrete is passivated by the ferric oxide film in high alkalinity of concrete[1]. This protective layer gets breakdown, when the chloride ion concentration at the rebar reaches the threshold level and/or the cover concrete is carbonated[2–4]. The competition of hydroxyl ions with chloride ions causes the local adsorption of chloride ions on the passive film and leads to the local dissolution of passive film. The depassivated sites may have lower potential as compared to the other passivated (cathodic) sites on the rebar surface and act as anodic sites. The potential difference along the reinforcing steel in concrete leads to the establishment of an electrochemical cell with anodic, cathodic sites and concrete pore solution as an electrolyte[2]. The following half-cell reactions must take place at the anode and cathodic regions in corrosion phenomenon with the same rate:

- First half cell reaction: The oxidation of iron from Fe to Fe²⁺ releases free electrons. The positively charged ferrous ions pass into the pore solution and free electrons reach the cathodic site through the rebar.
- Second half cell reaction: The liberated electrons from the oxidation of iron are consumed by the cathodic sites and combine with the water and oxygen to form hydroxyl ions

The hydroxyl ions formed by the reduction of oxygen at cathodic region travel through the electrolyte (concrete pore solution) and combine with ferrous ions to form ferrous hydroxide (Fe(OH)₂). This
Fe(OH)$_2$ gets precipitated on rebar surface and undergo further reactions to form rust based on the pH value of concrete pore solution, availability of water, and oxygen. It is important to note that the chloride ions present in concrete responsible for localized pitting corrosion of reinforcement, but the neutralization of concrete by the carbonation induces the generalized corrosion. Half-cell potential, concrete resistivity, and corrosion current density are the main parameters to be considered to evaluate the corrosion state of the rebar in concrete[5]. From the above parameters, the corrosion current density ($I_{\text{corr}}$) only gives quantitative information about the corrosion of rebar in concrete. Electrochemical techniques, namely, linear polarization resistance (LPR), potentiodynamic (Tafel), Galvanostatic pulse, Electrochemical impedance spectroscopy, Harmonic analysis, can be used to determine the $I_{\text{corr}}$ values through polarization resistance and Stern-Geary equation[6]. Although $I_{\text{corr}}$ value varies based on the adopted technique, LPR technique is considered as most preferable due to its low effect on the rebar condition. The obtained $I_{\text{corr}}$ from the LPR technique is purely instantaneous. This technique utilizes the linear relationship of potential ($E$) and current ($I$) and at around the corrosion potential ($E_{\text{corr}}$). The slope of E- I curve (polarization curve) at $E_{\text{corr}}$ is known as linear polarization resistance ($R_p = \frac{\text{d}E}{\text{d}I}$). On the rebar embedded in concrete, the $R_p$ values can be determined by polarizing the rebar with small potential (typically ±20 mV) from $E_{\text{corr}}$. The obtained $R_p$ value is related to $I_{\text{corr}}$ using Stern-Geary equation as follows[7]:

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

(1)

Stern-Geary constant $B$ comprises anodic and cathodic Tafel slopes. In the case of rebar in concrete, generally $B$ value is considered as 26 mV in active corrosion state or 52 mV in a passive state of rebar. There is an uncertainty in LPR measurements due to the ohmic drop caused by the finite electrical resistance of concrete and significant distance between rebar and the external electrode[8]. During the flow of polarization current from rebar (working electrode) to the counter electrode, through the concrete causes a potential drop ($E_p = IR$, where I: polarization current, R: uncompensated resistance). This potential drop is generally referred to as an ohmic drop (IR), electrolyte resistance or solution resistance. This voltage drop exists during the electrochemical measurements on rebar embedded in concrete due to the flow of current through finite resistivity of concrete. The corrosion measurements ascertained without considering the ohmic resistance leads to too small $I_{\text{corr}}$ values, which are erroneous[9]. The importance of ohmic drop in cathodic protection is also significant. In cathodic protection, corrosion is reduced by polarizing the cathodic sites towards the anodic potential. When the cathodic protection current is flowing through the soil/concrete, the IR drop caused by an applied current within the cathodic region supports in reducing the cathodic protection current[10]. Having in mind the flow of current through concrete, it appears reasonable that electrical conductivity of concrete pore solution, microstructure, moisture content and temperature are playing a role in IR drop. However, the pore solution chemistry depends on pH and ionic species like chlorides, sulphates, and other alkali metal ions.

As the problem due to IR drop is well known, several IR compensation methods have been developed. Nevertheless, the problem is still neglected by many users, especially for the corrosion measurements of reinforced concrete structures in the field. Keeping this in view, an attempt has been made to estimate the IR drop error level in LPR measurements to highlight the importance of IR compensation in corrosion studies on reinforced concrete structures.

In this work, the error level due to the IR drop in LPR measurements is investigated. The IR drop errors of various samples are discussed concerning the admixed salt type like chloride, sulphate.

2. Experiment

2.1 Materials and specimen preparation

Three concrete mixtures were prepared with three different admixed solutions and water-cementitious material (w/cm) ratio 0.48. River sand, which complied with Zone II and natural coarse aggregate with a nominal maximum size of 20 mm, were used in this study. As well as ordinary Portland cement meeting Indian standards IS: 12269 -2013[11] was used. The concrete mixtures were contaminated with 5% of NaCl as chloride source, 2% of MgSO$_4$ as sulphate source, and a combination of both the salts. The salts
were added in mix water while preparing the concrete mixtures. Rebar of diameter 10mm was embedded centrally in concrete slab specimens of size 320mm x 320mm x 52 mm. Rebar was cleaned to remove all the rust on the surface of the rebar before placing it into the concrete. The two ends of the rebar were protected with a neoprene tube such that the middle portion of length 250mm is exposed to monitor the corrosion measurements. After demoulding, the reinforced slab specimens were exposed to curing for 28 days, after that exposed to normal ambient laboratory conditions for two months.

2.2. Corrosion monitoring technique

Corrosion monitoring instrument ACM (Advanced Corrosion Monitoring, U.K) Gill AC guard ring serial no.1824-sequencer was used to determine the corrosion current density of the rebar in slab specimen. Before testing, the slab specimens were immersed in the water for 10 hours to avoid the noise caused by too much dryness. The LPR technique was used to monitor the \( I_{corr} \) values on slab specimens using the guard ring. The other details about the guard ring assembly were discussed elsewhere[3]. Rebar in slab specimen was polarized to ±20 mV from the corrosion potential with the scan rate of 0.1 mV/second. The LPR technique was performed with and without the IR compensation technique.

\[ R_{P,M} = \frac{B}{R_{p} + R} \]  
(2)

\[ \Delta = \frac{I_{corr} - I_{corr,M}}{I_{corr,M}} = \frac{R}{R_{p}} \]  
(3)

To demonstrate the error level caused by the uncompensated polarization, the results obtained by the laboratory experiments have been discussed in this section. Figure 1 depicts the differences between \( R_{P} \) and \( R_{p,M} \) values, which are measured by compensated and uncompensated LPR techniques, respectively. Figure 2 and figure 3 shows the solution resistance and relative errors of different concrete mixes made with chlorides, chlorides plus sulphates and sulphate solutions. From figure 1, it can be observed that the \( R_{p,M} \) values are higher than the \( R_{p} \) values. It is due to the well-known fact that the uncompensated \( R_{p,M} \)
accounts both $R_p$ and solution resistance. As the minimum $R_p$ value represents the higher corrosion, from figure 1, it can be observed that the concrete admixed with chloride shows higher corrosion as compared to the concrete admixed with chlorides plus sulphate solution. While observing the uncompensated polarization value (i.e., $R_{p,M}$ values), the difference between chloride samples and chlorides plus sulphate samples is not significant, but it is more significant in compensated resistance. While observing figure 2, the resistance of cover concrete or electrolyte resistance is approximately the same between the chloride and chloride plus sulphate contaminated concrete samples, although the compensated polarization resistance ($R_p$) is varied. It can be an important observation since it explains that the error is not an absolute value of solution resistance. Oldham et al. [13] reported that the error could be substantial even in high conductive electrolyte solution if the polarization resistance value is low. The high corrosion of rebar in chloride contaminated concrete is attributed to the availability of high chloride concentration as compared to the concrete contaminated with chlorides plus sulphate solution[14]. The polarization resistance and electrolyte resistance values are higher in concrete, admixed with magnesium sulphate solution alone. This can be attributed to the low electrical conductivity of sulphates present in concrete[15].

Figure 3 shows the corrosion current density values measured by both compensated and uncompensated LPR technique. Due to the reciprocal relation between $R_p$ and $I_{corr}$ values, $I_{corr}$ values are increased with decrease of $R_p$. It is observed that the concrete contaminated with chlorides has shown the higher corrosion and the concrete contaminated with sulphates has shown lower corrosion. It confirms that the participation of sulphates alone in corrosion mechanism is negligible. It is also observed that $I_{corr,M}$ of rebar in concrete contaminated with chlorides and sulphates is not similar with $I_{corr}$ values, which are obtained by compensated LPR technique. It is evident that the effect of IR drop is most considerable in corrosion monitoring in reinforced concrete structures. The error due to IR drop can be illustrated clearly with the difference between corrosion current density values measured by both compensated and uncompensated technique, as shown in figure 4.

![Figure 3](image3.png)  
**Figure 3.** Corrosion current density values with and without IR drop compensation LPR technique.

![Figure 4](image4.png)  
**Figure 4.** Relative error in corrosion measurements due to IR drop in concrete contaminated with different salts.

The relative error in chloride, chloride plus sulphate and sulphate admixed concrete mixes is 14%, 9.6% and 7.8%, respectively. High relative error was observed at high corrosion values, that is the rebar in chloride contaminated concrete mix. However, the less relative error was observed in sulphate contaminated concrete specimens, in which the corrosion is less. From this observation, it is clear that the IR compensation needs to be considered when the corrosion of reinforcement is high.

4. Conclusion
1. $R_p$ and $R_{p,M}$ values measured on chloride and chloride plus sulphate contaminated concrete are confirmed that the IR drop error is not an absolute value to explain the solution resistance of the sample.
2. The IR drop error is more for chloride contaminated concrete as compared to other concrete contaminated with combined chloride plus sulphate and pure sulphate solutions, due to the high corrosion rate in a chloride environment.
3. As compared to chloride contaminated concrete samples, the sulphate contaminated samples show less IR drop error due to the low electrical conductivity of sulphates.
4. The high corrosion in chloride contaminated concrete as compared to the chloride plus sulphate contaminated concrete is due to the availability of high chloride concentration.

5. References

[1] Yang L, Xu Y, Zhu Y, Liu L, Wang X and Huang Y 2016 Evaluation of Interaction Effect of Sulfate and Chloride Ions on Reinforcements in Simulated Marine Environment Using Electrochemical Methods Int. J. Electrochem. Sci. 11 6958
[2] Ismail MAE 2003 Corrosion of reinforcement - An Application of concrete technology from theory to practice
[3] Raghu babu U and Kondraivendhan B 2019 Impact of sulphate on chloride-induced corrosion of steel in concrete Indian Concrt. J. 8–17
[4] Raghu Babu U and Kondraivendhan B 2020 Application of Statistics to the Analysis of Corrosion Data for Rebar in Metakaolin Concrete Learning and Analytics in Intelligent Systems vol 2, ed S C Satapathy, K S Raju, and G A Tsihrintzis (Cham: Springer International Publishing) pp 162–9
[5] Palaniswamy N and Vedalakshmi R 2010 Analysis of the electrochemical phenomenon at the rebar–concrete interface using the electrochemical impedance spectroscopic technique Mag. Concr. Res. 62 177–89
[6] Vedalakshmi R and Thangavel K 2011 Reliability of Electrochemical Techniques to Predict the Corrosion Rate of Steel in Concrete Structures Arab. J. Sci. Eng. 36 769–83
[7] Stern M 1957 Electrochemical Polarization J. Electrochem. Soc. 104 559
[8] Walter G W and Centre T 1977 Problems arising in the determination of accurate corrosion rates from polarization resistance measurements 17 983–93
[9] Oeßner W, Berthold F and Guth U 2006 The iR drop – well-known but often underestimated in electrochemical polarization measurements and corrosion testing 455–66
[10] Angst U M and Büchler M 2018 Impact of IR drops on the -850 mvcse cathodic protection criterion for coated steel pipes in soil J. Pipeline Syst. Eng. Pract. 9 1–11
[11] Bureau of Indian Standards 2013 Ordinary Portland Cement, 53 Grade-Specification (First Revision) IS 122692013
[12] Xu J, Cao Y, Jiang L, and Feng W 2016 Error Estimation of Linear Polarization Resistance Measurement Caused by IR Drop for Reinforcement Corrosion in Concrete 866 14–9
[13] Oldham K B and Mansfeld F 1973 Corrosion rates from polarization curves: A new method Corros. Sci. 13 813–9
[14] Shaheen F and Pradhan B 2015 Effect of chloride and conjoint chloride – sulfate ions on corrosion of reinforcing steel in electrolytic concrete powder solution ( ECPS ) Constr. Build. Mater. 101 99–112
[15] Sipilä K, Bojinov M, and Stanislowski M 2015 Effect of chloride and sulfate additions on corrosion of low alloy steel in high-temperature water Electrochim. Acta 173 757–70