Review of Various Methods Used for Corrosion of Steel in Cement Compared to Vipulanandan Impedance Model

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Abstract

In this study corrosion of steel monitoring in cementitious materials in previous studies were reviewed. In previous studies half-cell potential, mass loss, electrochemical impedance, galvanostatic pulse methods were used to monitor the corrosion of steel. Testing of the steel in cement specimens were carried out from 5 days to 15 years in water, NaCl and air atmosphere. Vipulanandan equivalent circuit electrical method with two probes was used for cement-steel casing corrosion study, where the bulk corrosion and surface corrosion were quantified.

1. Introduction

Structural failures due to corrosion of steel not only impact the service life of the structure but also failures due to corrosion can cause economic losses. Construction industry is heavily impacted by the effects of corrosion as the corrosion of steel bars could cause deterioration of the steel and reinforced concrete structures, thus results in failure (Kashani, et al., 2013). Corrosion of steel reinforcement results in fracture cracking, spalling of concrete cover, reduction of flexural and shear strength and reduction of ductility of the material (Kashani et al. 2013). As per the U.S Corrosion study conducted between 1999-2001, around $276 billion losses were related to the direct cost on metallic corrosion and this was 3.1% of the U.S. Gross Domestic Product (GDP) of 1998 (Koch, et al., 2002). The global cost of corrosion was estimated as US$ 2505 Billion, and this was 3.4% of global Gross Domestic Product (GDP) in 2013 (Koch, et al., 2016). This justifies the importance of monitoring and quantifying the steel corrosion in infrastructure.

2. Objective

The overall objective was to review the existing methods of corrosion monitoring of steel in cementitious material. Also, the Vipulanandan Impedance model for detection and monitoring of corrosion of steel in cementitious materials was evaluated.

3. Methodology

3.1 Existing methods for corrosion monitoring

For corrosion monitoring, corrosion coupon weight loss method, electrical resistance probe method, electrochemical sensors, ultrasonic testing of wall thickness method, magnetic flux leakage method, electromagnetic sensors, passive wireless sensors, optical fiber sensors and pipe inspection gauge are used (Wright, et al., 2019). According to ASTM standards, pitting corrosion evaluation, potentiodynamic polarization resistance measurements, and galvanic corrosion tests are used to evaluate the corrosion of steel.

Corrosion detection in reinforcing steel bar in cementitious materials was studied by numerous researchers. (Chousidis, et al. 2022; Birbilis and Holloway 2007; Díaz, et al. 2018; Li, et al. 2020). The summary of studies on corrosion of steel in cementitious material are summarized in Table 1. In the studies, half-cell potential, mass loss, electrochemical impedance, galvanostatic pulse methods were used. For the electrical methods A/C and D/C current with two and three electrode system were used. Testing of the specimen were carried out from 5 days to 15 years in water, NaCl and air atmosphere.

Table 1: Summary of studies on corrosion of steel in cementitious material

Reference	Medium	Steel type and shape	cement type	Composition	Corrosion method	Testing period	Corrosion Parameter	Remarks
Wootton, Spainhour and Yazdani 2003	5% NaCl	Reinforcing steel bar	NA	Two types of epoxies used, Concrete cylinders	Half-cell potential measurements, Visual inspection, Mass loss	5-65 days (Until failure)	Potential (E), Mass loss ratio (per day)	1.DC current
Birbilis and Holloway 2007	0.6 M NaCl, water and dry (air)	Reinforcing steel bar	NA	Concrete	Galvanostatic pulse method	NA	Polarization resistance, Time constant (RC)	1.Three Electrode system
Díaz, et al. 2018	Marine atmosphere (air)	Rebar	CEM I 52.5R	Cement mortar, water/cement = 0.5, sand/cement ratios = 3	Corrosion potential (Ecorr), Electrochemical impedance spectroscopy (EIS)	15 years	Corrosion Current (Icorr), Equivalent circuit parameters	1.Three Electrode system 2. AC current, 1-100000 Hz
Hassan, Elkady and Shaaban 2019	3% NaCl	Reinforcing steel	Ordinary Portland cement	NA	Electrochemical test	15 days	Corrosion rate from the parameters	1.Two Probe 2. AC current

Reference	Medium	Steel type and shape	cement type	Composition	Corrosion method	Testing period	Corrosion Parameter	Remarks
Li, et al. 2020	40˚C temperature and 3.5% NaCl (Wetting and Drying cycles)	Reinforcing steel bar	Type I 42.5 Portland cement	Water to cement ratios (w/c) 0.4 and 0.5, Cement: Sand = 1:1	Half-cell potential measurement and Polarization curve, Mass loss of steel	100 days	Corrosion potential, corrosion current, Mass loss rate	1.Two Probe 2. AC current
Chousidis, et al. 2022	3.5% NaCl, partially placed	B500C Steel reinforcement bar	CEM I 42.5N cement	Cement: sand: total water = 1:3:0.65	Half-cell potential, Corrosion current, Mass loss	180 days	Corrosion Current, Gravimetric mass loss	1.DC current
Rao and Sasmal 2022	3.5% NaCl	Reinforcing steel bar	Ordinary Portland cement	Smart cementitious composite, Water/cement 0.4	Conductance, Impedance	13 days	Peaks in the conductance and impedance curve	1.Two Probe, copper sheets, 2.DC and AC current
Remarks	NaCl, water and air were used	Reinforcing steel	Ordinary Portland cement	Cement, concrete	Half-cell potential, mass loss, Galvanostatic pulse method, electrochemical method, electrical impedance method	5 days-15 years	Corrosion current, mass loss rate, equivalent circuit parameters, time constant (RC)	1. Two probe, three electrode system 2.D/C, A/C current.

3.2 Vipulanandan Impedance Model method

Cement and steel composite was placed in water bucket is shown in Figure 1. For the molds, four insertions were made for the wire probes (C1, C2, C3 and C4) as shown in Figure 1. A bottom cutout was made for the steel cylinder to go through (Steel contacts M1 and M2). For the steel and wire are connected (M1 and C3) to the LCR meter as shown in Figure 1. The measurements of the resistance and reactance values were taken using LCR device for the frequency range of 20 Hz to 300 kHz.
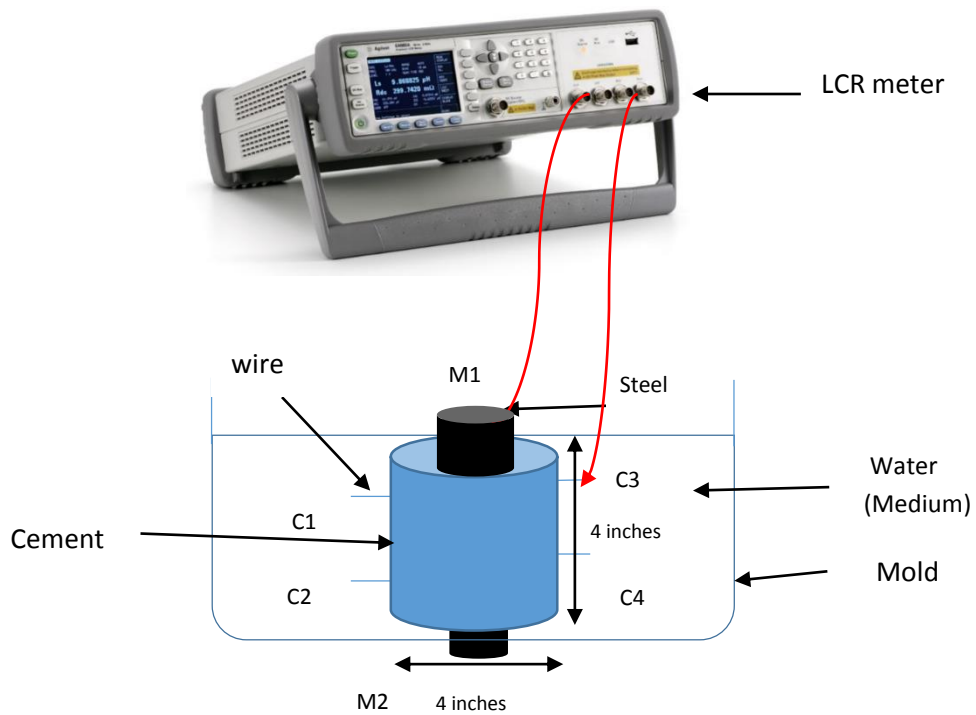

Figure 1 Cement Steel Casing wire configuration

Figure 2 shows the experimental and modelled Zreal vs frequency for steel-cement configuration. Based on the measured impedance-frequency plots a suitable equivalent circuit was chosen. The equivalent circuit for steel in cementitious material is shown in Figure 3.

Here the bulk material is taken as resistance only while the two contact points are taken as a resistor and capacitor in parallel.
Impedance equation for given equivalent circuit diagram of corrosion model.

$$Z = R_b + \frac{R_c}{1+\omega^2 R_c^2 C_c^2} + \frac{R_i}{1+\omega^2 R_i^2 C_i^2} \text{ ---(1)}$$

The above circuit equation can be used and the bulk resistance, contact resistance and contact capacitance values for all the probe configurations were computed by optimizing the model impedance data points using available programs. The steel surface corrosion is as follows.
  1. Steel Surface Corrosion = RiCi --(2)

2. M1-M2 measured gives the bulk resistance of steel and also the corrosion changes in resistance and resistivity.
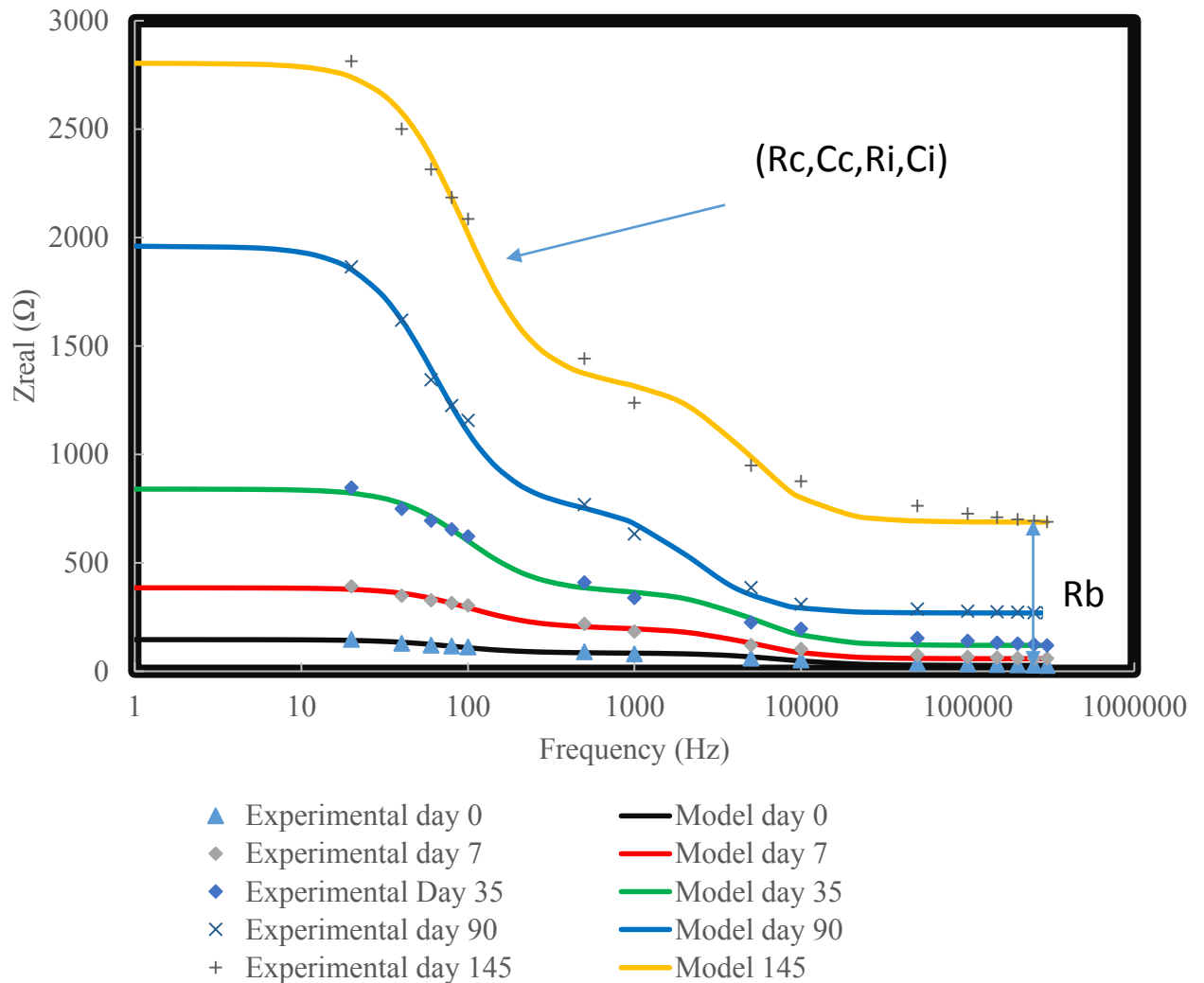

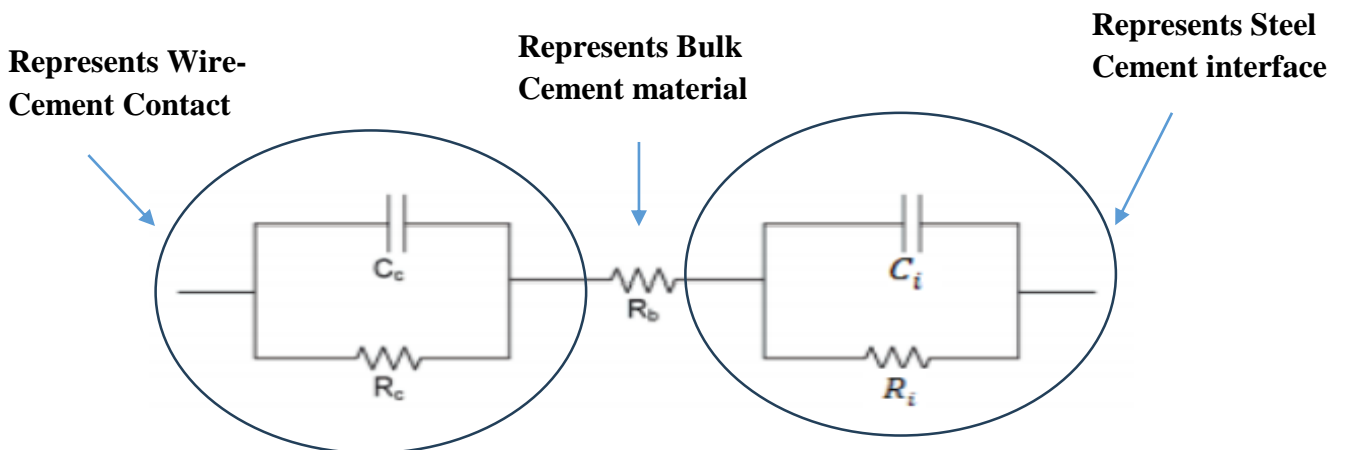**Figure 2 Experimental and modelled Zreal vs frequency for steel-cement configuration.**

Figure 3 Equivalent circuit diagram of corrosion model

4 Conclusions

1. Testing of the steel in cement specimens were carried out from 5 days to 15 years in water, NaCl and air atmosphere.
2. In previous studies half-cell potential, mass loss, electrochemical impedance, galvanostatic pulse methods were used.
3. For the electrical methods A/C and D/C current with two and three electrode system were used.
4. Vipulanandan equivalent circuit for case 2 can be used for cement-steel casing, where the bulk is represented by resistor and contacts were represented by two parallelly connected resistors and capacitors.
5. The bulk resistance, contact resistance and contact capacitance of all wire configurations were determined by optimizing the circuit formula. For Steel -wire configuration, the bulk resistance, contact resistance, contact capacitance, interface resistance and interface capacitance were determined using optimization of the circuit formula.

5 Acknowledgement

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