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ORIGINAL RESEARCH ARTICLE

IMPACT OF CORROSION MONITORING TECHNIQUES ON DURABILITY ASSESSMENT IN REINFORCED CONCRETE: A REVIEW

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ABSTRACT

Corrosion of reinforcement in concrete structures remains a durability issue in structural engineering with the increasing cost of repair and maintenance. The mechanism and factors influencing reinforcement corrosion in concrete with various electrochemical monitoring techniques including non-destructive and destructive techniques have been considered. Also, the roles of sensors have been reviewed to determine the monitoring technique that proved most effective in determining corrosion parameters and more practicable for the assessment of concrete durability. Electrochemical impedance spectroscopy and linear polarization resistance techniques showed great performance in evaluating corrosion kinetics and corrosion rate respectively while gravimetric weight loss technique provided accurate measurements. No single monitoring technique showed to be the ultimate technique, and this calls for more research work in the development of more dynamic monitoring tools capable of considering all possible corrosion factors in the corrosion monitoring process.

1.0 Introduction

Steel reinforcement corrosion in concrete structures is a dominant factor causing structural failures under short-term and long-term considerations leading to loss of serviceability and eventual collapse of concrete structures. Several research works focused on reinforcement corrosion, detection, testing and repair (Tuutti, 1982; Broomfield, 1997; Rodriguez et al., 1997; Val, 2007; Li et al., 2019; Shahid et al., 2020) with the advancement in detection and testing methods due to its reoccurrence and increasingly high cost of maintenance repairs in many structures including marine structures, bridges, and other structures. For instance, it has been reported that corrosion damage costs in the USA is worth about half a million dollars and globally about $100 billion per annum (Broomfield, 1991; 1997; Li et al., 2007).

Reinforcement corrosion is mainly induced by the presence of chloride ions in concrete causing complete and localized de-passivation of the rebar and when carbon dioxide in the air reacts with cement matrix and the resulting interstitial solution is acidified while in contact with rebar (Montemor et al., 2003). Reduced electrical resistivity, permeability issues owing to water-cement ratio, microcracks, contaminated concrete mix and inadequate concrete cover are other factors influencing reinforcement corrosion propagation in concrete (ACI C222, 1996; Bazant, 1979). In addition, Permeation, absorption and diffusion are harmful transport in concrete. Concrete under loading leads to microcracks especially as stress levels increases (Okenyi 2018), Rebar reduction in its cross-section, loss of the bonding force between rebar and concrete, volumetric expansion caused by corrosion producing split-tensile stresses (Coronelli and Gambarova, 2004; Auyeung et al., 2000; Broomfield, 1997) including other alterations to steel ductility are processes leading to the damage of reinforced concrete structures (Zhu and François, 2014). Numerous evaluation techniques for corrosion investigation in reinforced concrete have been used over time in both research and practice.

The goal has always been to be able to establish the relationship existing between corrosion growth and time as means of adequately predicting the service life of a structure undergoing degradation considering the various methods that are now in use. This paper focused on corrosion in reinforced concrete structures holistically with a focus on the review of corrosion monitoring techniques used to determine the most effective and how these techniques were useful in detecting concrete durability issues and its overall service life prediction.

1.1 Mechanisms of Steel Corrosion in Concrete

It is important to note that the process of steel reinforcement corrosion in concrete is electro-chemical through an exchange of electrons and movement of charges especially as it occurs in an aqueous medium (Uhlig and King, 1972). In this scenario, the concrete pore water serves as that medium i.e., the electrolyte and the electrode consisting of a composite of combined anode and cathode is the corroding steel surface which is electrically connected along the body of the steel reinforcement as shown in Figure 1, forming the electrochemical cell and the reaction occurring at both electrodes are named "half-cell reactions" (ACI C222, 1996). The corrosion formation mechanism is either microcell or macrocell dictated by the distance between the anodic and cathodic reactions.

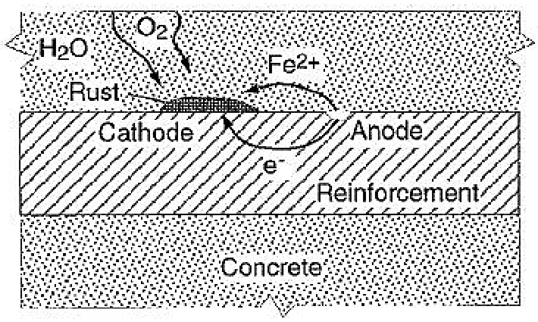

Figure 1: Corrosion formation in concrete (Carino, 1999)

At the anode, an oxidation reaction occurs causing the degradation of the steel in which iron *Fe* is oxidized to form iron cations affected by aggressive environment conditions, pH of the electrolyte as shown in reaction equation (1):

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

While at the cathode, a reduction reaction occurs balancing equation (1) in which hydrogen ions are reduced to form hydroxyl anions in reaction equation (2) in the presence of oxygen, pH around steel surface and a decreased ambient temperature.

$$1/_2\, O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-} \quad (2)$$

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The anodic and cathodic reaction products when combined is what produces the surface film that passivates the reinforcement steel. Some previous research showed that the passive film is favoured by the presence of iron oxides, Fe_3O_4 (magnetite) and Fe_2O_3 (Hematite) (Hansson, 1985; Kruger and Calvert, 1967) while others claim it is by Ca $(OH)_2$ (Page, 1990; Montemor et al., 1998).

Corrosion breakdown mechanism models include an adsorption-displacement model which proposes that passive film is destroyed by its adsorption of chloride ions (Cl^-) with a simultaneous displacement of oxygen ions (O_2^-) (Böhni and Uhlig, 1969). Also, the chemico-mechanical model suggests that surface tension is reduced by Cl^- thereby forming cracks (Sato, 1982) while the migration-penetration model proposes the migration of ions of Cl^- to take the place of O_2^- and cause voids leading to pitting formation and pit growth (Chao et al., 1981).

In conclusion, understanding the mechanism by which corrosion of steel occurs in concrete helps to study the damage mechanics to see the damage evolution mechanics on a microscale and could serve to predict the service life of reinforced concrete experimentally or using computational techniques.

2.0 Methods

2.1 Steel Corrosion Monitoring Techniques

Various reinforcement corrosion evaluation techniques have been used and discussed. By simply visualizing a concrete structure undergoing corrosion, basic information regarding nature of corrosion could be determined such as cracks, concrete spalling, and rusts (Pullar-Strecker, 1987) although better detection methods were proposed by other scholars (Stratfull et al., 1975; Manning and Holt, 1980). In recent times, this method remains non-economical and takes time as more advanced methods have been developed with minimal setbacks. Of all the various factors used in corrosion rate monitoring, including change in pH, chloride content monitoring, change in temperature, strain, acoustics etc., the most important and quantitative way is measuring the current rate I_{corr}, owing to the single fact that reinforcement corrosion in concrete is an electrochemical process. Thus, both destructive and electrochemically non-destructive corrosion assessment method has been considered.

2.1.1 Galvanostatic Pulse Method (GPM)

This is a non-destructive transient method where a small amount of anodic current pulse usually in the range of 10 to 200 μA is applied between the rebar and a counter electrode positioned on the surface of the concrete for 5-10 s. Electrochemical potential V_t from the polarization of steel is obtained using equation (3) (Montemor et al., 2003) and plotted against time of polarization. It should be noted that when polarization occurs and anodic and cathodic current is measured, this method is referred to as Potentiodynamic polarization.

$$\mathrm{V}_t = I_{ap} \cdot R_\Omega + I_{ap} \cdot R_\Omega \left[1 - (\exp(\frac{-t}{R_p \cdot C_{dl}}))\right] \tag{3}$$

where t is the time, R_p is the polarization resistance and C_{dl} is the double layer capacitance at the reinforcement surface, R_Ω is the ohmic resistance between the surface electrode and the steel bar while I_{ap} is the applied current.

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From Figure 3, R_p is obtained from the curved segment by curve fitting and the Stern-Geary equation in equation (4) and Faraday's law of electrochemical equivalence in equation (5) is used to obtain the corrosion rate with a typical 2D surface plot in Figure 4.

$$\mathrm{I}_{Corr} = \frac{B}{R_p} \tag{4}$$

$$\text{Corrosion rate } \left(\frac{\text{m}}{\text{yr}}\right) = 11.6\frac{I_{corr}}{A} \tag{5}$$

B is based on Tafel constants and has values of 52 and 26 *mV* for passive steel and steel in concrete respectively (Andrade et al., 1986). *A* (*cm*^{2}) being the area of steel under the counter electrode.

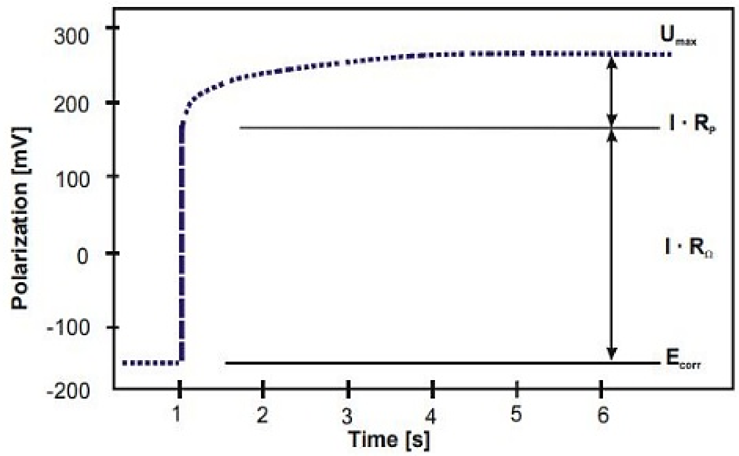

Figure 3: Electrochemical potential of steel against time (Sørensen and Frølund, 2002)

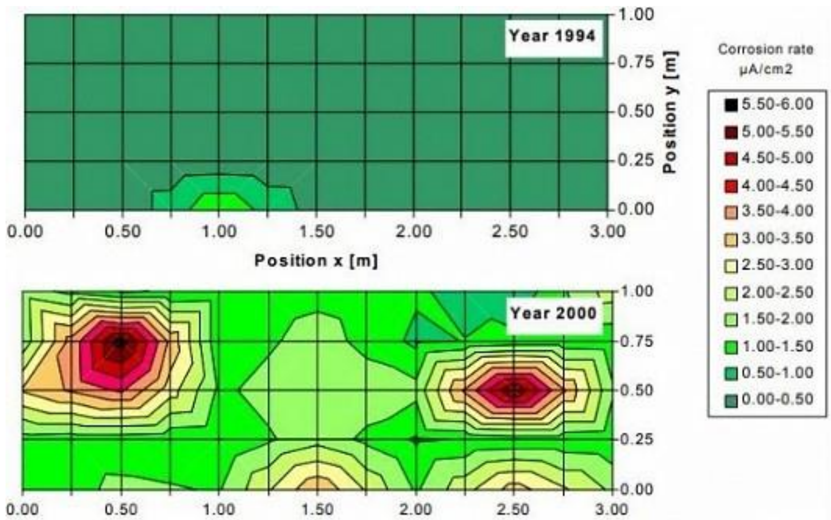

Figure 4: Corrosion rate using GPM over six years (Sørensen and Frølund, 2002)

2.1.2 Linear Polarization Resistance (LPR)

In this method, a polarization potential value of 10-30 *mV* is applied below the Open circuit potential E_{oc}at a scan rate of 0.1 *mV/s* scan rate and the current density *i* (current response divided by surface area of the electrode) were obtained (Daniyal and Akhtar, 2020). The resulting relation is quasi-linear owing to the small potential being applied (Millard et al., 2001). Thus, Linear polarization resistance R_p is obtained from the slope of the graph of potential against current density depicted in Figure 5 and finally, equation (4) is used to determine the corrosion rate.

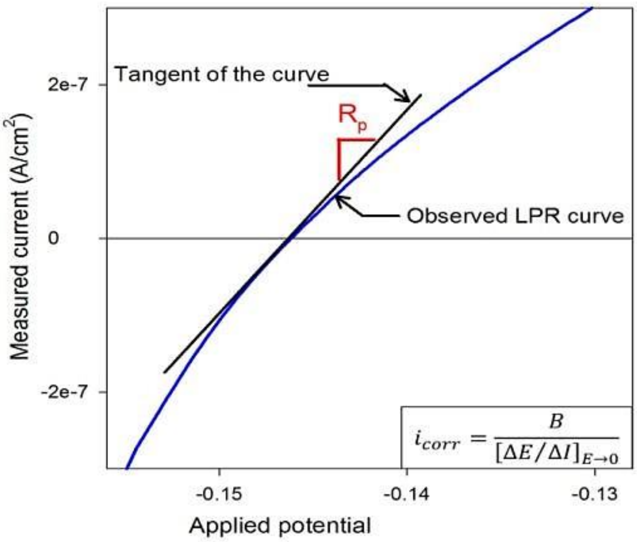

Figure 5: Typical polarization resistance curve (Karuppanasamy and Pillai, 1995)

2.1.3 Half-Cell Potential (HCP)

This qualitative corrosion monitoring technique is otherwise known as open circuit potential where a voltmeter measures the potential difference at different points between the steel and another half, a reference external electrode usually immersed in copper/copper sulphate ($Cu/CuSO_4$) or silver/silver chloride (Ag/AgCl) solution and concrete is kept wet to ensure electrical connection (Figure 6). Table 1 indicates the probability of corrosion from HCP measurements conforming with ASTM C876 (ASTM C876, 2015). This method does not specify the corrosion rate, it only states the probability of corrosion (Yeih and Huang, 1998).

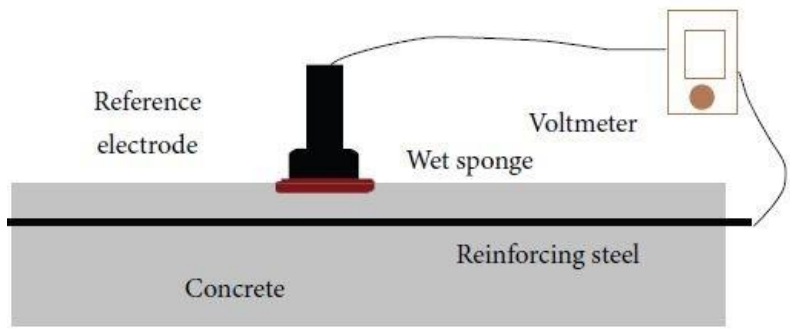

Figure 6: Typical half-cell potential set-up (Verma et al., 2014)

Table 1: Probability of Corrosion for $CuSO_4$ (ASTM C876, 2015)

S. no.	Half-cell potential (mV)	Probability of corrosion
1	>-200	10%
2	-200 to -350	50%
3	<-350	90%

2.1.4 Time Domain Reflectometry (TDR)

This method is usually used in steel strands in prestressed concrete structures as well as cable in bridges in which a sensor wire is run along the steel forming a parallel conductor line and an electromagnetic pulse of voltage is sent through the line in a set up in Figure 7 and reflected from the end and the magnitude of reflection is given in equation (6):

$$r = \frac{Z-Zo}{Z+Zo} \tag{6}$$

where *r* is reflection coefficient, *z* is impedance and z_o is the characteristic impedance of steel strand.

Pitting corrosion, surface corrosion and voids disrupt a change in the electromagnetic pulse with *p3* (Figure 7) due to high impedance. Thus, the circuit properties such as series resistance *R*, series inductance *L*, capacitance *C* and conductance *G* are monitored (Liu et al., 2001). Corrosion detection is marked by a reduction in radius at a corrosion location with an increase in impedance which is detected by the time domain reflectometry and more reflection translates to more damage. This method measures the extent and length of corrosion as well as voids.

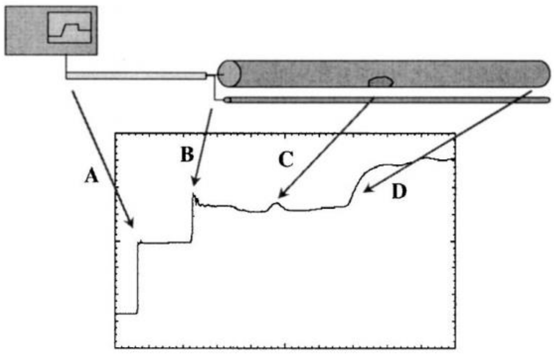

Figure 7: Pit corrosion monitored by time-domain reflectometry Curve (Liu et al., 2001)

2.1.5 Ultrasonic Guided Waves (UGW)

This is a method still in use presently for detecting corrosion progression in steel reinforcement in concrete. Mechanical pulse waves are transmitted into the concrete rebar by using contact transducers (piezoelectric transducer PZT, Annular series transducer, full, electrode transducer) of frequency 0.1 MHz and 1 MHz, one acting as the transmitter of the ultrasonic waves and the other is the receiver used in different excitation modes. By comparing changes in signal amplitude and pulse velocity, damage in rebar can be quantified. Longitudinal placement of transducers at low frequency at 0.1 MHz detects corrosion initiation the best because it produces longer wavelength and resolution loss is easily detected and while frequency at 1 MHz detects pitting in rebar Sharma and Mukherjee, (2010) with a typical response depicted in Figure 8 for two excitation modes. This method has other numerous applications and could also be used in freeze-thaw cycle monitoring in detecting concrete ageing (Alawode, 2018).

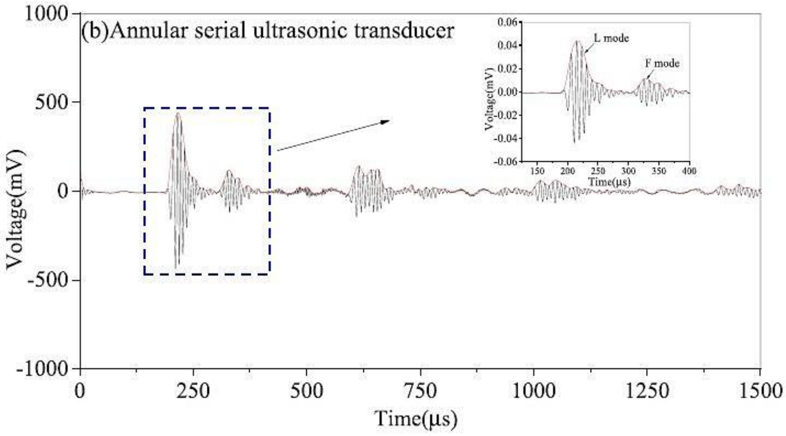

Figure 8: Typical ultrasonic time-domain spectra response (Liu et al., 2019)

2.1.6 X-Ray Diffraction (XRD)

X-rays and Gamma-rays are radiographic non-destructive method employed in monitoring corrosion and other microstructure defects in reinforced concrete structures by evaluating its crystallographic structure. These rays are electromagnetic monochromatic radiation penetrating concrete through release photons directed to the mapped area which is transformed by a fluometallic converter which captures the defects in rebar, its size, location, voids in rebar and concrete by measuring X-ray diffraction angle (Song and Saraswathy, 2007; Burkett, 2018). Safety precaution should be ensured when in use. A typical XRD response (Figure 9) shows corrosion products composition to be rusts.

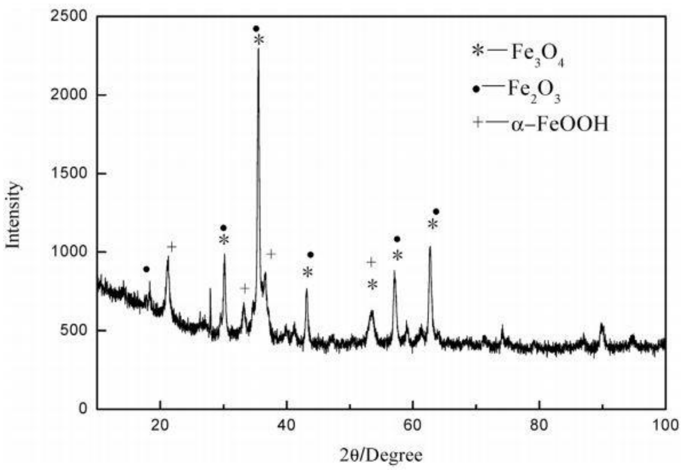

Figure 9: Typical XRD response spectra for corrosion (Liu et al., 2017)

2.1.7 Electrochemical Impedance Spectroscopy (EIS)

This method is otherwise known as alternative current (AC) impedance spectroscopy. An alternating voltage of about 10-20 *mV* which is the excitation potential is applied to the steel reinforcement as the AC and phase angle is recorded with their different frequencies *f*. Impedance *Z* which is the ratio of AC voltage to AC is obtained (Stern, 1957). The graph in Figure 10 referred to as either the impedance spectrum or Nyquist plot, impedance has a real or resistive (*Z'*) and imaginary part (*Z''*) which is capacitive or inductive measured at frequencies between 100 kHz and 10 *M*Hz (Daniyal and Akhtar, 2020). This response is likened to the one obtained in an electrical circuit (Randels circuit) where corrosion takes place as an electrochemical process. From Figure 10, R_c is the ohmic resistance of concrete and the diameter is resistance at which the steel dissolves called transfer resistance R_{ct}.

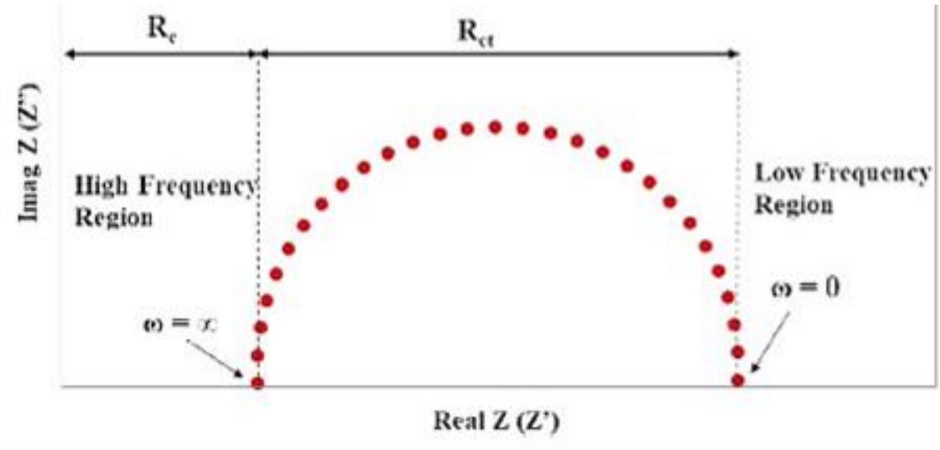

Figure 10: Basic Nyquist response for steel (Ribeiro and Abrantes, 2016)

Free elections movement towards steel surface anions and movement towards cathode in solution forms two layers capacitance C_{dl}. Thus, impedance is given in equation (7) (Natarajan and Ramakrishnan, 2007) as:

$$Z = R_c + \frac{R_{ct}}{1+j\omega C_{dl}R_{ct}} \quad (7)$$

Where j is $\sqrt{-1}$ and ω is $2\pi f$.

At low frequency, the circuit becomes a direct current (DC) circuit but when the frequency is high i.e. when ω is infinity, the circuit becomes AC and from the difference between DC and AC, true polarization resistance becomes R_{ct} and a lower R_{ct} value means corrosion values are high and the reverse is also true (Ribeiro et al., 2015).

2.1.8 Gravimetric Weight Loss (GWL)

This method is a destructive method used in determining the corrosion rate in a concrete structure. The test is carried out by guidance of ASTM G1-03 (ASTM G1-03, 2004) where the specimen is broken, and rebar is cleaned and immersed in Clarke (solution composed of 93% concentration of HCl, 5% $SnCl_2$, 2% Sb_2O_3) after which it is distilled with water and dried in air to completely remove corrosion products. Initial weight is taken before placement in concrete and after breakage, final weight is recorded. The corrosion rate is obtained from equation (8) (Odio et al., 2014) given as:

$$I_{corr} = \frac{K \times \Delta W}{A \times T \times \rho} \quad (8)$$

Where ΔW is weight loss, A is exposed surface area (cm^2), T = Time of exposure (hrs.), K is unit conversion constant given as 8.76×10^4 (for mm/year) and ρ = density (g/cm^3).

This method is suitable for long term corrosion detection.

2.1.9 Electrical Resistivity Method (ERM)

When the reinforcement steel is de-passivated, the continuity of corrosion rate is influenced by concrete's electrical resistance. This forms the basis of measurement of resistivity which is given as the electrical resistance multiplied by the length between probes (Millard and

Harrison, 1989). The Wenner four-probe measuring device Wenner, (1915) which is now adapted for resistivity measurement as shown in Figure 11 where AC, *I* is applied to two outer probes and a potential difference *V* between the inner probe is recorded and resistivity is determined using equation (9) (Gowers and Millard, 1999).

$$Resistivity(\rho) = ka\frac{V}{I} \quad (9)$$

Where *a* is space between probes and *k* is a geometric factor given as 2π.

A review of the relationship between resistivity values and steel reinforcement risk of corrosion is still inconclusive from previous research conducted because different factors such as concrete ageing, microstructure, water-cement ratio, temperature, and moisture content affect resistivity and this shows recommendation for more research on the subjecting order to arrive at a more stable scale of resistivity measurement and corrosion determination (Chen et al., 2014).

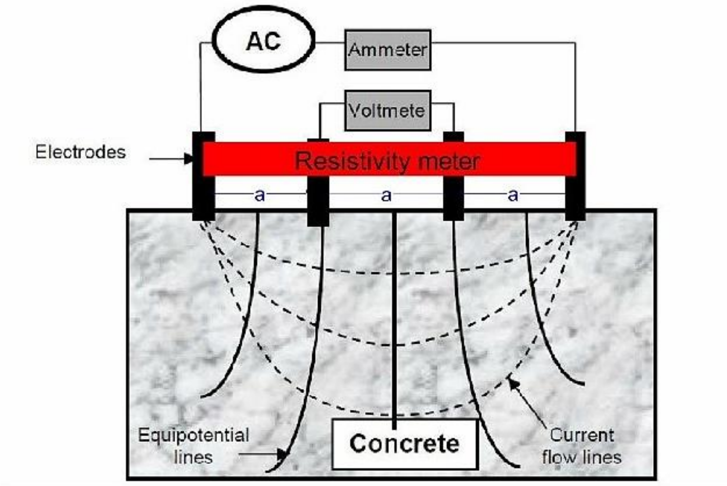

Figure 11: Wenner four-probe device measuring concrete resistivity (Carino, 1999)

2.2 Monitoring Sensors and Other Monitoring Techniques

The use of sensors (preferably non-invasive) come to play in cases where the discussed known instruments are not practicable, and corrosion needs to be monitored at specific regions in concrete materials while it allows for the juxtaposition of parameters to be measured to obtain a better understanding of corrosion rate and its effect in assessing durability in recent times. Some of the sensors studied in the past by authors include chemical microsensors, ring sensors, chloride sensors (Guth et al., 2001; Raupach and Schießl, 2001; Yun et al., 2004) as well as other automated mapping sensors in detecting rebar location, length of rebar in concrete structures (Chamberlain, 1992; McFee et al., 1996) and infrared thermography which is now in use in detecting voids and delamination in concrete but the challenge is that these methods haven't given detailed corrosion rate analysis.

Fiber optic sensors are currently more employed in reinforcement corrosion detection majorly because they have good sensitivity over a large area, resistant to chemical effects, free of electromagnetic influence and are cheap to produce and have and are still being been explored by various authors (Grattan et al., 2007; 2009; Zheng et al, 2009; Jagtap and Nayak, 2020). Sun et al. (2014) used optical fiber Brillouin sensor to determine rebar corrosion in a concrete column where the Brillouin optical time-domain reflectometer measured the strain and cracking pattern and used it in detecting and identifying corrosion location. Piezoelectric ceramic (PZT) sensors are also as advantageous as the fiber optic sensors in diagnosing corrosion damage shown by previous authors (Park and Park, 2010; Rathod and Mahapatra, 2011) When necessary, one or more sensors could be combined to see how effectively corrosion rate in rebar could be detected as carried out by Rathod and Mahapatra (2011).

Other monitoring techniques involve the use of Embedded Corrosion Instrument (ECI) (Figure 12) which is an intrusive corrosion sensor monitoring LPR, HCP, ESM, temperature and chloride ion concentration remotely saving a lot of data manipulation, site visits and costs have been considered, including the smart pebble sensor for chloride ion monitoring (Reis and Gallaher, 2006; Watters et al., 2003) and others techniques applied to reinforced concrete bridges include corrosion penetration monitoring system and V2000 monitoring cable (Agrawal et al., 2009). In conclusion, the use of sensors in corrosion monitoring holds great promise especially being able to detect corrosion rate remotely. Thus, it is recommended that more research should be conducted especially in combining the sensors to be able to cover all parameters needed in accurately predicting timely corrosion impact and assessing serviceability of concrete structures.

Figure 12: ECI in operation (Song and Saraswathy, 2007)

3.0 Results and Discussion

3.1 Overview of Corrosion Monitoring Techniques on Concrete Durability

To date, corrosion problems caused especially in the infrastructures sector is still major concern and various monitoring technique are still being applied. However, the review of the methods used so far in detecting corrosion in reinforced concrete structures from rigorous work has been reported in Table 2. These provide the benefits and limitation to these methods in effectively assessing the serviceability of concrete structures and as a means of predicting and discussing the most effective method and giving further recommendations on improvement.

Table 2: Review of corrosion techniques used

Reference	Research Conducted	Observation on durability	Remark
Montemor et al. (2003)	Conducted research to determine the chlorides critical level and factors constituting to steel corrosion using LPR, GPM, EIS and potential measurement.	The critical level was reached in concrete as Cl^- reacts with Fe, causing pit growth and the pH of concrete was a major factor.	EIS provided the most effective method under consideration although measurements took time which was compensated for by GPM although fluctuations were experienced.
Bäßler et al. (2001)	Presented results from the monitoring of steel reinforcement corrosion rate comparing natural corrosion to measured corrosion in the laboratory using GPM device.	Real-life corrosion parameters showed a correlation with measured parameters for short-term measurements.	Long term results for corrosion lifetime evaluation lost correlation as measured parameters became different and GPM device could not account for that showing further need in improving sensitivity.
Sørensen and Frølund (2002)	Discussed the effectiveness of using the GPM technique in accurately estimating corrosion rate in concrete structures.	Corrosion rate was detected quickly in steel reinforcement and it agrees with gravimetric weight loss results, although identifying active corrosion area took time.	The swiftness of GPM could help in the timely detection of deterioration and chloride environment presence will affect durability. Thus, GPM should be improved to consider causative factors.
Moreno et al. (2004)	Performed an investigation to determine the effect of carbonation and Cl^- on corrosion of steel reinforcements using LPR technique.	Critical chloride levels were detected above which pitting took place while increased pH of concrete improved resistance to localized corrosion.	LPR measurements effectively measured chloride-induced corrosion rates and were effective even at low chloride levels although this may be due to oxygen evolution potential being overestimated.
Romano et al. (2013)	Worked on monitoring the degradation occurring in reinforced concrete structures in chloride environments using LPR, ERM and potential measurements.	There was a serious decrease in polarization resistance value which matches the resistivity values in the corrosion initiation phase as chloride content increases.	LPR and ERM measurements at different depths in concrete also have an impact on the corrosion rates obtained and more studies could help detect the role of depth in the mechanism of transportation of aggressive materials in concrete.

Pradhan and Bhattacharjee (2009)	Researched on the performance of different rebar placed in different cement type concrete in chloride condition using LPR, GWL and EIS.	The dominant factor influencing corrosion was chloride content and admixtures improved corrosion resistance.	LPR appeared to have given a better value of corrosion current density showing its better performance over EIS.
Elsener (2001)	Studied the use of HCP mapping in assessing localized corrosion caused by chloride deposit in reinforced concrete.	Results depicted re-passivation of steel after repair work.	HCP mapping technique was only able to ascertain the chance of corrosion and was marked by the lower negative potential which did not necessarily indicate corrosion. Thus, its ability to predicting durability could not be completely relied upon.
Carino (1999)	Considered the use of non-destructive techniques including HCP, ERM and LPR in investigating corrosion in concrete.	For HCP, measuring potential gradients was a more effective way of corrosion measurement. ERM indicated active corrosion although not rate and LPR gave quick corrosion rate results.	LPR proved to be a very useful means of accessing durability but not service life due to change in time conditions and resistivity which is crucial to corrosion combined with HCP results gives a better understanding of reinforced concrete corrosion.
Pour-Ghaz et al. (2009)	Presented work on a tool to better interpret measurements obtained from HCP mapping in concrete structures.	It was recommended HCP and resistivity values should be combined for better information on corrosion rate.	This research attempted to solve the problem of inadequate information obtained from using HCP alone earlier identified for corrosion prediction but validation and model development on key corrosion determining factor is needed.
Liu et al. (2001)	Reported experimental results in the novel application of TDR to monitoring corrosion in prestressed high-performance bridge beams	The method showed to effectively locate and detect corrosion damage levels from in-situ readings and even from application to laboratory-scale samples.	TDR is useful although there are energy loss issues when measuring lengthy samples and further research is encouraged on reinforced concrete samples and how to effectively translate results to detect corrosion rate on a long term basis.
Furse et al. (2009)	Researched using TDR as a non-destructive method of determining faults in prestressed	Spectral TDR proved to function well even in anchors placed in concrete and shown to	Long-range measurement issues were addressed increasing signal-noise ratio to detect invisible faults and the

	anchors	measure faults up to a maximum of about 48m.	combination of EIS with TDR could prove very effective in determining corrosion rate.
Hunsperger et al. (2003)	Performed an investigation to determine steel corrosion in structures which are already existing externally using TDR.	Voids were shown to be critical to corrosion propagation as it harboured moisture and salts and affected signal return monitored by TDR.	Internal monitoring of corrosion using TDR provides a more accurate means. Best measurement using this method comes from direct measurement of steel reinforcement and ways to ensure this in existing structures should be improved upon.
Du et al. (2017)	Studied how corrosion developed in steel embedded in concrete using UGW and piezoelectric transducers to monitor the stages.	Wave velocity was inversely proportional to corrosion rate. Initial corrosion, rapid corrosion and further corrosion development were the three stages identified.	The mass loss had to be combined with acoustic parameters to determine corrosion rate although piezoelectric was able to boost reception of a better signal for time and frequency domain spectra showing that PZT's are important to corrosion monitoring
Yeih and Huang (1998)	Discussed the evaluation of corrosion issues in reinforced concrete members using UGW technique.	Amplitude attenuation in ultrasonic testing was shown to vary with thickness loss giving good record of corrosion rate when combined with the AC impedance method.	If corrosion occurs, rust or microcracks will also occur changing amplitude. More effort is recommended for testing larger concrete samples and relating amplitude with other electrochemical parameters to prove corrosion detection.
Sharma and Mukherjee (2010)	Reported results from the monitoring of early-stage reinforcement corrosion in concrete considering UGW and acoustic emission sensors.	Acoustic emission sensors proved effective in detecting initial corrosion while UGW served to detect surface corrosion from pitting corrosion	UGW proved to be able to measure the extent of corrosion but unable to detect corrosion presence at early stages although its combination with acoustic sensors was effective
Hossain (2005)	Studied the corrosion resistance of three types of concrete mixes and used XRD, HCP, LPR, GWL technique in monitoring corrosion in a steel bar.	Active corrosion was detected using HCP and rate by LPR, but volcanic admixtures were good corrosion inhibitors.	XRD provided quantitative measurements in terms of composition showing a reduction in calcium hydroxide content to show good performance of volcanic admixtures.

Takahashi et al. (2005)	Described the composition of corrosion products formed reaction between iron and sodium chloride using in-situ XRD analysis	Iron oxides were main constituents formed from corrosion affected by precipitation and dissolution of Fe.	XRD only provided information on the formation mechanism of corrosion and the quantification of its constituents.
Burkett (2018)	Presented the outcome of a study on the application of XRD to characterize corrosion to provide a timely solution.	Natrojarosite and akaganeite were found to be constituents of corrosion using a portable XRD device.	Building upon this device to measure rate from quantities determined in minutes could prove extremely invaluable to corrosion monitoring.
Ribeiro and Abrantes (2016)	Performed an investigation on the use of EIS as a non-destructive technique in studying corrosion in reinforced concrete.	Angular frequency theory was applied to EIS result interpretation and it gave a more improved interpretation	EIS provides accurate measurement about corrosion rate, its mechanism, and changes to rebar. This research is only a further improvement on a well-established technique to boost easier interpretation.
Ismail and Ohtsu (2006)	Worked on determining corrosion rate in both high strength concrete and ordinary concrete using EIS, LPR and dynamic polarization in a chloride environment.	High strength concrete exhibited lower corrosion rate values when compared to ordinary concrete owing to lower w/c ratio in high strength concrete.	EIS results were lowest of the three, showing a difference in the way overall resistance of corrosion was measured and based on the inverse relationship between resistance and corrosion rate, one could argue the effectiveness of EIS method.
Dhouibi-Hachani et al. (1996)	Presented results obtained from the comparison EIS results between low frequency applied to steel and high frequency applied to concrete.	The frequency distribution model agreed with EIS results from the experiments.	Using EIS here was able to expose interaction between steel -surface resistances on corrosion rate and how it helped better measurement.
Bhaskar et al. (2011)	Studied reinforcement corrosion caused by chloride in cracked concrete and GWL was used for quantification as a destructive technique.	GWL readings indicated that crack presence influenced corrosion than crack width. Also, lower w/c ratio lowers steel corrosion.	This method of corrosion monitoring still proves to be effective in quantifying corrosion rate although it is destructive.
Azarsa and Gupta (2017)	Reviewed various relationship between electrical resistivity and reinforcement corrosion	The ERM measurements were affected by moisture and temperature and	ERM method is good in detecting active corrosion probability and rate, especially when combined with LPR

	in concrete.	further investigation was recommended.	showing. It is also useful in detecting corrosion potential and this fact is yet to be standardized.
Morris et al. (2004)	Sort to establish a standard corrosion determination value using ERM monitoring in reinforced concrete.	Results indicated active corrosion at 10 $k\Omega{\cdot}cm$ and passive corrosion at 30 $k\Omega{\cdot}cm$	ERM effectively evaluates the severity of corrosion but still needs to be combined with LPR to determine corrosion rate values.
Sadowski (2013)	Worked on the combination of ERM and LPR for effective service life prediction using a reinforced concrete slab sample.	The experiment showed three areas of slab having a 90% probability of corrosion, the second area showed uncertainty while the third area gave 10% corrosion probability.	The distribution of active corrosion was well depicted using this method and this method is good in terms of its possible application to new and existing structures.
Ha et al. (2004)	Described the use of different sensors applied to an assessment of corrosion and durability in concrete.	The role of sensors depended on the measurement of important factors including, chloride content, temperature, moisture etc.	As smart materials are being introduced, one major advantage is the ability to place it in structures and it holds promising results, and more works are being authored in this area.
Muralitharan et al. (2006)	Researched to check the electrochemical properties of Alkaline manganese dioxide, metal-metal oxide, and graphite sensors.	Alkaline manganese dioxide sensor showed the most stable potential measurements although chloride ions showed no effect on measurements.	These sensors were not affected by chloride and this is an advantage when being embedded in concrete and long-term research is recommended to confirm this.
Karthick et al. (2014)	Reported the results from the comparison between embedded sensors and sensors placed on a concrete surface to monitor corrosion in reinforced concrete.	The embedded HCP sensor gave lesser corrosion rate than the surface placed LPR probe.	This further proves the fact that lower corrosion rates when techniques are combined shows that method producing lower corrosion rate has better performance and it is affected by steel-concrete resistance.
Daniyal and Akhtar (2020)	Reviewed various electrochemical method for corrosion monitoring to see their performance in reinforced concrete.	Electrochemical methods were useful for both laboratory and in-situ measurements, GWL was the most efficient destructive method.	No individual method proved to be the best, but the combination of electrochemical methods was effective in monitoring corrosion

Verma et al. (2014)	Reviewed the value of HCP method and other corrosion monitoring techniques and their role in the durability of concrete structures.	HCP technique was shown to be the most applied technique and was useful in determining suitable protective measurement	HCP is also affected by different factors including cover to concrete and its combination with resistivity yields a better interpretation

Most of the methods considered in the literature has shown that often, different corrosion monitoring techniques have always been combined to obtain good results and this shows that no one method is most effective. Also, there is a need to consider more application of these methods in real-time monitoring and its applicability in offshore concrete structures where the impact of various environmental factors and mechanical factors combined impair durability.

4.0 Conclusion

Based on the review conducted in this study on the previous research and various corrosion monitoring technique and their principle of operation that has been applied especially over the last two decades, the observation of the results on durability obtained and the overall effect these techniques in accurately measuring corrosion rate and prediction, the following conclusions were made from the critical review:

- The electrochemical impedance spectroscopy method proved to be a very considerable technique when it comes to understanding the mechanics and kinetics of reinforcement corrosion as it provides an accurate polarization resistance value from reviewed papers who have applied this technique regardless of its time-consuming nature which could be reduced when combined with galvanostatic pulse method.
- Linear polarization resistance technique provided a very effective means of measuring corrosion rate which is also measured by other electrochemical technique including galvanostatic pulse, impedance spectroscopy, potentiodynamic tests but what made linear polarization unique was its ability to detect chloride content even at very small levels in concrete and more future is recommended on establishing an interpretation of its results, especially for service life predictions.
- Other corrosion monitoring techniques including time-domain reflectometry, use of piezoelectric transducers, ultrasonic guided waves, electrical resistivity method and use of sensors need further improvement in detecting early and long-term corrosion. Also, the impact of humidity, moisture and temperature need to be considered in new research as they hold the key future degradation assessment in concrete structures for different zones.
- Reinforced concrete corrosion is still a major problem in the civil engineering design and construction sector and more smart materials are currently being developed. From this review, specific monitoring technique proved excellent when considering specific needs such as understanding corrosion processes and monitoring corrosion rate and even detection, but no single method encompasses these factors. Thus, future work is recommended in combining core measured characteristics of other devices into building a workable monitoring unit which can perform all measurements.

Notation

AC	Alternating Current
ASTM	American Society for Testing and Materials
ϖ	Angular frequency, rad/s
Sb_2O_3	antimony (III) oxide
A	area, m^2
C	capacitance
Cl^-	chloride ions
G	conductance
Cu	copper
$CuSO_4$	copper sulphate
I_{corr}	corrosion rate, m/yr.
I	current, A
DC	Direct Current
ERM	Electrical Resistivity Method
ρ	electrical resistivity, Ohm ·m
EIS	Electrochemical Impedance Spectroscopy
V_t	electrochemical potential, µ
ECI	Embedded Corrosion Instrument
f	Frequency, Hz
GPM	Galvanostatic Pulse Method
GWL	Gravimetric Weight Loss
HCP	Half-Cell Potential
Fe_2O_3	hematite
HCl	hydrochloric acid
Z	Impedance, Ω
Fe	iron
LPR	Linear Polarization Resistance
Fe_3O_4	magnetite
O_2^-	oxygen ions
PZT	Piezoelectric ceramic transducer
V	potential difference, v
pH	Potential of hydrogen
R_Ω	resistance, ohm
L	series inductance
R	series resistance
Ag	silver
AgCl	silver chloride
B	tafel constants, mV/decade
TDR	Time Domain Reflectometry
$SnCl_2$	tin (II) chloride
UGW	Ultrasonic Guided Waves
XRD	X-Ray Diffraction

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