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CORROSION ASSESSMENT METHODS IN REINFORCED CEMENT CONCRETE

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Abstract. Worldwide huge amount was spent on infrastructure development projects, in which a major part is spent on demolishing deteriorated structures due to their reduction in serviceability due to various external factors. This may be attained by preventing reinforced cement concrete (RC) structures from factors that affect serviceability such as corrosion. The research community is developing various techniques to predict corrosion in RC structures to prevent the structure in the initial stages by carrying out maintenance work instead of going for the reconstruction of deteriorated structures. The corrosion of RC structures was mainly caused by chloride ions penetrating the structure or by carbonation. This coefficient can be used to predict the rate of corrosion in concrete. Electrochemical measurement, Eddy current, Half-cell potential measurement, etc., are the experimental techniques to forecast the corrosion rate in concrete reviewed. Recently various software's like Life 365, Thermos calc, Concrete Compass, etc., were developed to predict the corrosion rate in RC structures. This research paper reviews the effectiveness of the application of software to predict corrosion rate in RC structures by reviewing previous research works to identify an accurate method to be followed.

1 Introduction

Corrosion is commonly known as the wastage of metal due to the action of reactive agents. However, it is briefly explained as a destructive attack of material through a chemical or electrochemical reaction with its environment. The economic value and performance of reinforced concrete are the most significant material used in the construction industry. Corrosion of reinforcing steel degrades concrete structures by the results of chloride ions attacking the iron oxide protective film on the reinforcing steel or the concrete cover carbonation. Corrosion increases the cost of goods and services, both for the manufacturer and for the consumer, directly or indirectly. Bridge collapses, highway failure, structural damage, etc., are the results of the corrosion of reinforcing steel bars. Practical, theoretical, and software methods were developed to predict corrosion rate in concrete.

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To predict the future performance of the concrete structure in the present condition, test structure was used to gather information by applying these methods. The purpose of this paper is to discuss some of the methods available for corrosion assessment. Steel reinforcement embedded in concrete can diagnose the causes and harshness of corrosion using these techniques. This article discusses the latest corrosion studies performed by different researchers. At the end of this article, we have provided a brief comparison of various techniques. To better understand reinforced steel concrete, this paper reviews studies conducted by several investigators.

2. Corrosion Assessment by Practical Methods

2.1 Linear polarization methods

In 1957, Stern and Geary was first introduced the direct current technique as linear polarization resistance technique. In an electrochemical process, corrosion is one of the processes and it violates ohm's law. . When the ohm's law is applied, then the polarization potential be small[43]. Therefore, the response current will linear. The below graph, represent a typical voltage and density of potential.

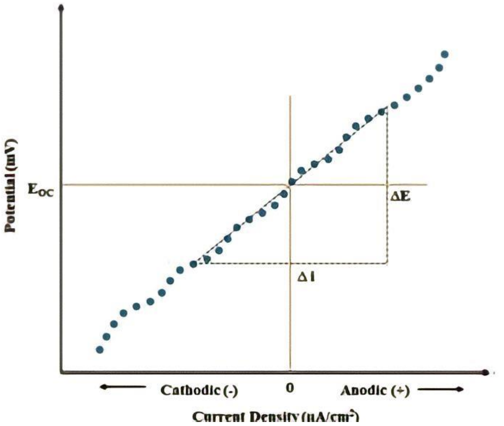

Fig.1.**Plot a linear polarisation.**

It is polarised at a rate of 0.1 mV/s between 0 and 20 mV from overpotential. The AC signal for IR correction has a wavelength of 10 kHz and a 20-mV amplitude. A Polarization LPR sweep for polarisation is on the sequencer list. by determining the Rp by tilting the potential-current curve. This Rp was computed using the variables Icorr and corrosion rate as mentioned in equation (1)[56]:

$$\mathrm{Icorr} = \frac{\mathrm{B}}{\mathrm{Rp}} \qquad (1)$$

Where B, Stern-Geary constant, 26 mV for active and passive reinforcement bar states; bias resistance, Rp; corrosion current, Icorr, A cm 2. Using the Icorr value, the corrosion velocity was calculated as the corrosion velocity by equation (2)

$$\mu\mathrm{m\ year} - 1 \ = 11.6 \ \times \ \mathrm{Icorr} \qquad (2)$$

2.2 Gravimetric weight loss measurement:

It is most commonly used destructive method and detailed guidelines for specimen preparation and corrosion rate assessment using gravimetric measures of weight loss have been specified [32][40]. From ASTM G1-03 gave a detailed guidelines for preparing specimens and evaluating corrosion rates through gravimetric weight loss are included [2]. The steel is weighed using a 0.1 mg precision computerised weighing balance before being inserted into concrete. After being exposed to a corrosive liquid for a predetermined amount of time, the steel from concrete sample was removed. The corroded steel must then be cleaned using the abovementioned method before being weighed once more. By applying the following relationship equation (3) to the weight loss value obtained, the corrosion rate (CR) can be estimated [13]:

$$CR = \frac{\mathrm{K\ X\ \Delta W}}{\mathrm{A\ X\ T\ X\ \rho}} \quad (3)$$

Where, ΔW is a weight loss in gram, A is a exposed surface area in cm^2, T is a Time of exposure in hours, ρ is a density in g/cm^3, K is a unit conversion constant. K = 8.76 × 104 (for mm/year) and k= 534 (for mils/year).This method is the most exact and accurate for estimating the rate of corrosion of steel and concrete structures due to the simplicity of testing replication. This extremely basic method reduces the likelihood of making minute errors. The sensitivity of mass loss measures is limited due to the fact that mass can only be measured with accuracy up to about 0.1 mg. This technique is also harmful and is often used after long periods of exposure, leading to a global corrosion rate[14].This method is also damaging and typically applied after lengthy exposure times, this method results in an average corrosion rate.

Table 1. Relationship between resistivity in concrete and risk in corrosion [14]

Concrete resistivity (kΩ cm) is the term for corrosion risk		
High	**Moderate**	**Low**
<5	5-12	>12
<6.5	6.5-8.5	>8.5
<7	7-30	>30-40
<10	10-30	>30
<20	20-100	>100
<10	10-100	>100-200
<5	5-20	>20
<8	8-12	>12

2.3 Eddy Current Techniques

The Eddy Current Technique is a Non-Destructive Technique (NDT). It is a low-frequency NDT. The setup is a single generator that provides the test coil sensor with the necessary frequency and voltage. The fundamental benefit of the ECT is the lack of physical contact between the sensor and the device. The configuration consists of a single generator that provides the test coil sensor with the necessary frequency and voltage[19]. In addition, a multimeter and oscilloscope are included for measuring voltage and signal quality, respectively. Eddy currents are agitated at a fissure or pit. As a result, the coil's back electromagnetic field is different than when there are no cracks.

This disruption may be recognized and intensified for a sound signal or visual display. The thickness of the rusted product must be smaller than the metal's skin depth to be considered thick. the limit of metal thickness where eddy currents are not allowed [22]. However, this approach can be utilised to identify surface defects. The steel approaches magnetic saturation when electromagnetic devices, which are frequently mounted on concrete surfaces, activate eddy currents produced by the steel reinforcement embedded in concrete [3]. It was investigated whether corrosion in RC structures might be found utilising an absolute transducer and ECT [19]. The experiment's results showed that ECT had a lower sensitivity for detecting corrosion in steel rebar.

2.4 Half Cell Potential

Describing the semi-cellular potential (HCP) of the American National Standards (ASTM C876) is a typical method for assessing the possibility of corrosion in the RCS [4]. The millivolt (mV) corrosion potential is often measured using semi-cells with copper sulphate and silver chloride (CES) electrodes, both of which are saturated calomel electrodes[14].Only when there is a direct link established between the testing apparatus and the reinforcing steel can the test be carried out. Another restriction is that it can only be used on uncoated reinforcing steel that is embedded in concrete and whose surface is devoid of a dielectric coating. The semi-cell consists of a copper rod floating in a saturated copper sulphate solution and has a non-reactive outer sleeve with a steel rod implanted in it. If there is no visible non - soluble crystal copper sulphate in the purified mix of water inside the half-cell, a saturated solution can be kept there. A semi-cell, also known as a reference electrode, is a device with a highly permeable tip made of ceramic or wood that allows it to retain moisture because of the capillary action of the membrane.

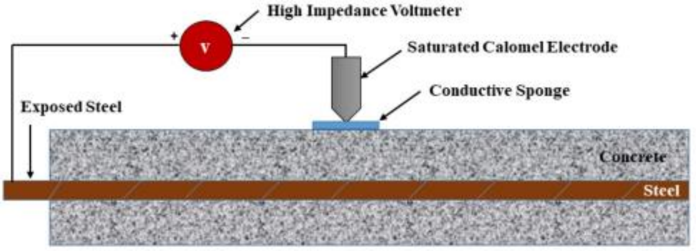

Fig.2. Setup for Half-cell Potential test

Corrosion potential is a measure of how likely a system is to experience corrosion. This table is used to figure out the measures. It should be kept in mind that, under certain circumstances, potential readings may display values less favorable than -350 mV without any discernible corrosion action taking place. This state might be caused by a polarization phenomenon due to reduced oxygen diffusion. The HCP reading of a concrete is influenced by both the resistivity and the matrix characteristics, which determine the concrete's resistance.[59]

2.5 Radiography

Radiography is the most common non-destructive technique for accessing reinforced concrete structures [54][37]. In radiography, shortwave radiation refers to electromagnetic beams that are invisible yet contain x-rays produced by x-ray machines and radioactive isotopes [39][37]. As x-rays propagate along a straight line instead of curving, the amount of energy attenuated by these rays depends upon three factors: the type of specimen, its thickness, and its density. Radiography can detect corrosion of the RC structure and can detect pitting corrosion as well as thickness loss[42][45][18]. Digital radiography uses some of the equipment for solid-state x-ray technology. They offer the percentage of corrosion in metals and are portable and quicker.

Table.2. Half-cell Potential value related to Corrosion condition.[14]

Corrosion Potential (E_{corr}) Values		Corrosion Probability(%)
(mV vs. SCE*)	(mV vs. CSE+)	
E_{corr}> -125	E_{corr}> -200	10 (low risk of corrosion)
-126 ≤ E_{corr}≤ -275	-200 ≤ E_{corr} ≤ -350	Intermediate
E_{corr}< -276	E_{corr}< -350	90 (high risk of corrosion)
E_{corr}< -426	E_{corr}< -500	Severe corrosion

Using X-ray data, it is feasible to keep track of how different corrosion products form as well as how cracks-induced corrosion starts and spreads over time. As a result, computer tomography (CT), a more reliable invention that provides high-resolution three-dimensional data and can help clarify the corrosion process in RC, was created in response to the need for improvement.Concrete samples can be studied using X-ray computed tomography to determine the type and extent of steel damage, even at a microscopic level[12]. Corrosion can be tracked using X-ray microcomputer tomography. This method can be used to monitor corrosion over time as well as the beginning and progression of cracks brought on by corrosion agents.

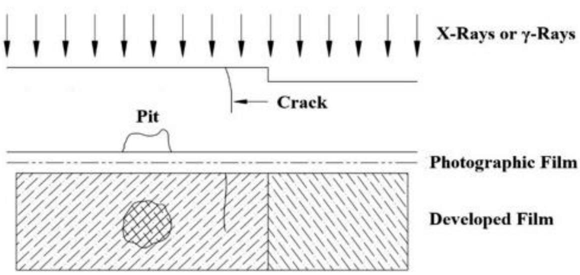

Fig.3. Radiography

2.6 Corrosion monitoring using sensors

In this method uses an optical fiber sensor with a fiber Bragg grating sensor to detect corrosion in steel rebar.A series of tests compared the weight loss rate of rebar (calculated using the gravimetric method) and the wavelength change visible from the grating in response to accelerated corrosion. This graph shows that the rate of weight loss in steel rebar increases with the width of the wavelength shift[24]. There have been a number of analytical and experimental studies carried out in various lab experiments to determine if fiber optic sensors are capable of detecting rebar corrosion in steel-reinforced concrete structures [23][25][26][58]. Several proof-of-concept studies have demonstrated that the use of piezoelectric ceramic patches can provide a means to identify corrosion in metallic structures, as evidenced by our work[51][52]. Due to the lack of reliable methods for determining the extent of corrosion damage after it was detected, the preliminary investigation was unable to determine the extent of corrosion damage after it is detecting.

3. Corrosion Assessment By Theoretical Methods

3.1 Fick's diffusion law

Corrosion of the reinforcements caused by chlorides occurs as a result of moisture and oxygen, which cause the reinforcement to corrode, when a specific amount of chloride build-up inside the structure exceeds a threshold value. It is widely known that even in skilfully built concrete buildings with small or nearly non-existent hereditary chloride content at the construction phase, over time the chloride concentration in the concrete increases significantly due to the infiltration of chloride ions from external sources. In aggressive environments, chloride ions enter concrete pores initially through diffusion, resulting in the movement of chloride along structures. This variable is taken to be a characteristic of hardened concrete.

Fick's diffusion rule is a frequently used model for modelling chloride infiltration and transport through concrete pores. Materials that are homogenous, isotropic, and inert can undergo fusion. It is believed that the mechanical characteristics associated with the process of diffusion are constant throughout time and are the same in all directions. These ideas are not entirely supported by concrete's heterogeneity, anisotropy, and chemically reactive characteristics (continuous hydration, micro-cracking process). Numerous engineering issues involving chloride intrusion, including those covered in this work, can be resolved by taking into account this simplification. Numerous engineering issues involving chloride intrusion, including those covered in this work, can be resolved by taking into account this simplification. The number of chlorides that are delivered into the concrete through a unit section of concrete in each amount of time (the flux F), in accordance with Fick's diffusion theory, is proportional to the gradient in chloride concentration measured along the section's normal direction.[10]. Then:

$$F = -Dc\frac{\partial C}{\partial x} \tag{4}$$

In the equation above, the increase in chloride concentration is countered by the diffusion of chlorides, therefore the negative sign. The diffusion coefficient for chloride is the name of this proportionality constant. Fick's first diffusion law is valid if the chloride diffusion coefficient is constant. The relationship is referred to as Fick's first general diffusion law in the absence of this.

This basic connection shouldn't be used in a number of different circumstances. Examples of situations where the spreading process may be permanent or has a history of reliance should be provided [7]. However, based on the limited information that has been collected thus far, the chloride diffusion into the pores of the concrete should be categorised as anomalous. Therefore:

$$\frac{\partial C}{\partial t} = \frac{\partial C}{\partial x}\left(-Dc\frac{\partial C}{\partial x}\right) \tag{5}$$

Applying Fick's second diffusion rule requires knowledge of how the chloride diffusion coefficient evolves in concrete subjected to chloride over an extended period. Despite this connection, a specific situation is taken into account in which the position, x, duration, and chloride content, C, have no impact on the chlorine diffusion coefficient. Fick's second law was expressed in this case in a straightforward manner.

$$\frac{\partial C}{\partial t} = Do\frac{\partial^2 C}{\partial x^2} \quad (6)$$

For semi-infinite domains with a homogenous mixture at the structure surface, the differential equation previously provided has the following solution:

$$C(x, t) = C0erfc[\frac{x}{2\sqrt{D_o t}}] \quad (7)$$

Due to the presence of interconnecting pores and micro cracking, concrete is not homogenous. As hydration progresses, the diffusion rate will alter with time. Fick's law is therefore a poor model for this phenomenon. When diffusion is one-dimensional, Fick's law offers an intriguing strategy.

3.2 Nernst Planck equation

The design of the transit path was explicitly taken into account rather than being combined with the diffusion since the ions' diffusion coefficients in the pore solution were assumed to be concentration-dependent. It demonstrated that electrically accelerated ionic transport has high tortuosity. In idealized models, geometric tortuosity is better understood by accounting for the correction factor. We also explain how the boundary conditions change during the accelerated migration test of reactions near electrodes. It is because transient boundary conditions need to be considered.Modified PNP models are validated using several OPC concretes containing a range of water-cement ratios and supplementary cementing materials and fillers.

3.2.1 Ionic transport accelerates the numerical modelling

This article provides an overview of the numerical models that have been used to describe electrically induced charge transfer through concrete. Based on what they can't do and what they might change.

(i) Separating the impacts of microstructure from the diffusion coefficient's concentration dependence.
(ii) Ion transit lengths under electrically driven migration accurately represented.
(iii) Details are provided regarding the impact of transient local carrier circumstances.

The procedure describes a practical approach to applying PNP equations to simulate accelerated ionic transport via various porous media. The study considersa few aspects that are frequently disregarded yet have been shown to have a major impact on results.
The PNP equation-based modelling of chloride ion movement in concretes under the influence of a applied electric potential will undergo a number of alterations [38]. Then use a methodical approach without making any changes to the utilised diffusion rate, micro structural parameters, or chlorine binding coefficients.

4. Corrosion Assessment By Software Methods

4.1 Life-365

Life 365 software predicts the duration between corrosion initiation and its need for repair. It can the ability to calculate construction costs as well as predicted repair costs throughout the course of a structure's complete design life. [57]Geographical location, building type, exposure type, concrete cover depth, water-cement ratio, fly ash, ground granulated slag, silica fume, corrosion inhibitors, steel type, whether coated or uncoated and membrane presence are just a few of the inputs that Life-365 software considers. [17]

Life 365 carried analyses in the software, which can be split into four steps as follow;

i. Initiation period (t_i) forecast the corrosion initiation time.

ii. The time it will take for corrosion to progress to an undesirable level is measured by the corrosion propagation period (t_p). The first repair time(t_t) is equal to the addition of the initiation periods (t_i) and propagation periods (t_p):$t_t = t_i + t_p$

iii. The repair schedule will be calculated throughout the structure's design life after the first repair.

iv. To estimate the life cycle cost, determine the price of the concrete, the price of the corrosion protection system, and the price of future repairs.[57]

Chloride ions' entry into the concrete cover depth, which is the active stage of corrosion, will cause the steel's passive corrosion layer to disintegrate. It is called the initiation period (t_i) and is the amount of embedded steel in an adequate quantity to an active corrosion state on the steel. A concrete structure's propagation period (t_p) is the adequate time necessary for sufficient corrosion to cause significant damage.

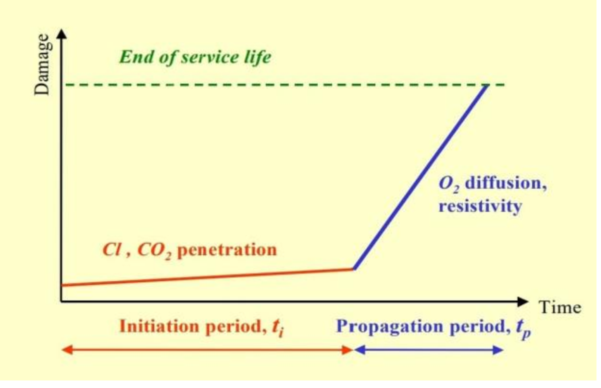

Fig.4. **Structures reach their end of service life based on Life 365 estimates[57]**

According to Life 365 software, corrosion protection techniques include silica fume, corrosion inhibitors, epoxy-coated steel, water-cement ratio, concrete covers, and a membrane over the structure. Life 365 Service is an industry-wide team that created the cutting-edge computer software program known as Life Prediction Model, which has a substantial impact on the industry's economically resilient concrete buildings.[57]

4.2 Thermo-calc

Using Thermo-Calc, alloy corrosion susceptibility can be studied, including aqueous corrosion, salt corrosion at high temperatures, metal dusting, internal oxidation, coating degradation, and molten salt corrosion. It is the development of corrosion-resistant alloy compositions and thermal barrier coatings (TBCs).[33]

4.2.1 Application of Thermo calc - Pourbaix Diagram Calculations for Pure Substances

Using Thermo-Calc, predictions can be made with the Pourbaix Diagram Module. The alloy composition and alloy composition determine the solution chemistry. A graph of 2.25Cr-1Mo steel shows the regions associated with immunity (H2 Gas Reducing Area), passivity (Fe2O3 and Fe3O4), and corrosion-prone regions. Data from traditional handbooks correspond nicely with the results.[55] Supercritical water is more corrosive than traditional reactor water solutions. It places challenges on a design by requiring materials that maintain strength at high temperatures and are resistant to both corrosion and irradiation. This figure shows a calculation of oxide formation and stability as a function of the partial pressure of oxygen. This calculation reveals that 12Cr steels can form a critical layered oxide under reactor operating conditions.

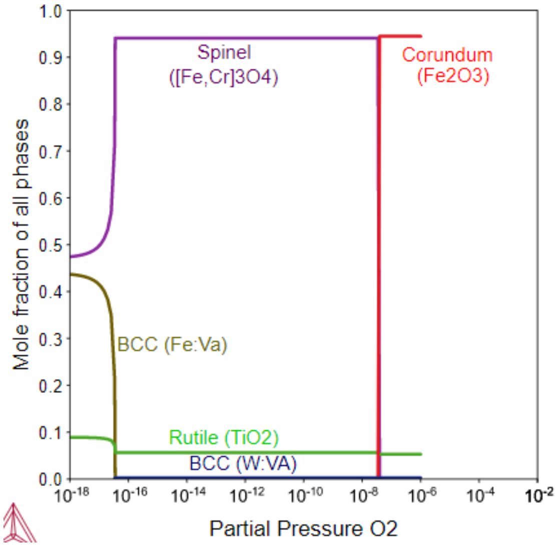

Fig.5. High Temperature Oxidation in Supercritical Water Reactor Service.

4.3 Concrete Compass

Model and predict concrete corrosion with a concrete compass. A Variety of concrete structures, such as buildings, parking lots, roadbeds, bridge decks, bridge substructures, concrete structures, and a variety of industrial facilities, corrode due to corrosion of the reinforcing steel.[9] Concrete corrosion causes cracks, stains, spalling, and ultimate structural weakness. In terms of concrete corrosion modeling and reinforced Concrete life prediction, Concrete-Compass is the only iOS and Android app on the market that is independent of devices and operating systems. Designers, architects, engineers, consultants, operation personnel, maintenance, and inspection engineers can quickly determine the concrete corrosion rate, the crack width at different depths of concrete cover from the concrete surface to the reinforcing steel, and the remaining life of the RC structure, anytime, anywhere, on any device running any OS without the need to install or download anything.[41] RC structures had designed to have a certain life, and Concrete-Compass can predict the minimum cathodic protection polarization used to reduce the corrosion rate.

A concrete corrosion model is provided by Concrete-Compass software using the following critical factors: structure age, maximum crack width allowed by code, concrete tensile strength, compression strength, rebar diameter, concrete cover thickness, water cement ratio, concrete temperature, cathodic protection, service environment, half-cell potential, concrete resistance.The Concrete-Compass software generates the following outputs: Prediction of corrosion current density, Predicting the corrosion rate, Cumulative rebar diameter loss, Remaining rebar diameter, Carbonation depth, Remaining life of the structure, and Prediction of corrosion rate.[9] Minimum CP polarization requirements at concrete surface, reinforcement, and midpoint of cover thickness, relative bond strength (MPa) of reinforcement corrosion, corrosion reduction factor by cathodic protection, which indicates how effective cathodic protection is, rebar position effect, and corrosion type effect. When the corrosive current density is measured, RC structures are predicted based on the service environment and corrosion current density. Although the concrete resistivity data is provided, the corrosion potential density of the reinforcement bars is not measured. A Concrete-Compass model predicts the crack width and the remaining life of RC structures by modeling concrete resistivity and environmental factors.[41]Engineering design, concrete corrosion prediction, cathodic protection design, optimization, and remaining life prediction of concrete structures under varying service environments are just a few of the powerful applications of Concrete-Compass.

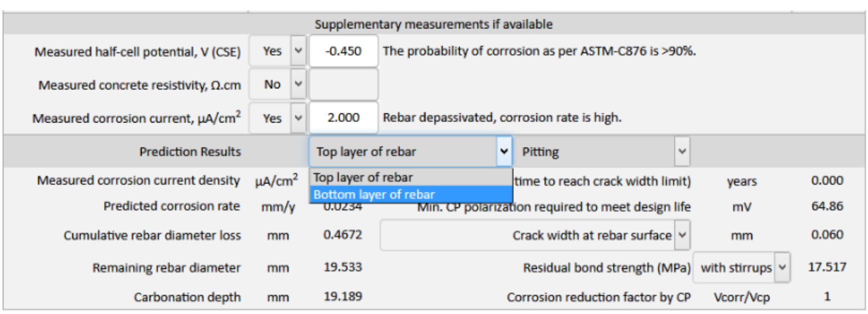

Fig.6. *Concrete compass supplementary measurements.*

5. Comparison of Corrosion Evaluation Methods

Experimental methods mainly focuses on the potential measurement in predicting the propagation of corrosion in reinforced concrete structures, which is easier to determine. Cathodic and anodic zones in steel-concrete structures, as well as the possibility of corrosion of reinforced concrete, are detected via surface potential monitoring. Resistivity measurement and sensors can be provided in the potential measurement method to deduct the corrosion of the reinforcement. Theoretical approaches used in Fick's Law include Nernst Planck Equation. The corrosion of reinforcements caused by chloride ions happens in the presence of moisture and oxygen when the accumulation of chloride inside structures reaches a certain level and there is little to no chloride inherited during construction. By allowing chloride ions from outside sources to enter the system slowly, the chloride content gradually increases. This simplification can be used to overcome the numerous engineering issues associated with chloride ingress, such as those covered in this article. By taking into consideration this simplification, a variety of engineering problems involving chloride intrusion, including those examined in this study, can be addressed. To achieve realistic portrayal of the real transport scenario, Nernst Planck developed an improved, self-consistent PNP concept for multi-species transportation in an accelerating migration test. It is assumed that the geometry of the transfer path and the ion diffusion coefficients in the pore solution are concentration dependent. To assist engineers in create stronger reinforced concrete structures without distracting the available structures to access the properties, software models can be used to develop corrosion-resistant structures.

Software tools such as Life-365, Thermo-calc, and Concrete Compass are employed in predicting rate of corrosion and its propagation in reinforced concrete. These programs provides the user with details on options and prices related to the durability and extended service life of concrete, geographical location, structure type, exposure type, intensity of clear concrete surface over reinforcement bars, water-cementitious material ratio, quantity and type of fly ash, surface slag, silica fume, or antifouling; type of iron, coated or uncoated; and appearance of membranes or sealers are among the general inputs that Life-365 takes into account. The Thermo-Calc have the application of Pourbaix Diagram Module and High temperature oxidation in super critical water reactor service, and it specify the both composite of the chemistry solution data from traditional handbooks corresponds well with the results. The super critical water is more corrosive than traditional reactor water solutions. It has required on challenges on design by requiring material and maintaining strength at high temperature and it’s resistant to corrosion and irradiation and Concrete compass are used for concrete corrosion modelling and life prediction which refers to corrosion of the reinforcing steels in concrete structures such as buildings, car parks, road beds, bridge decks and bridge substructures, concrete marine structures, and many industrial facilities. Designers, architects, engineers, consultants, operation personnel, maintenance and inspection engineers can quickly determine the concrete corrosion rate, the crack width at different depth of concrete cover from the concrete surface to the reinforcing steel, and the remaining life of the RC structure, anytime, anywhere, on any device running any OS without the need to install or download anything. Engineering design, concrete corrosion prediction and modelling, cathodic protection design and optimization, and remaining life forecast of RC structures are only a few of Concrete-numerous Compass's uses. This study considers things like reinforced concrete corrosion assessments and control approaches.

6. Conclusion

Corrosion should be controlled during the initial stage itself in order to improve the structural life rather than performing maintenance works after the corrosion reaches the critical levels. Corrosion initiation can be determined using various predictions techniques either directly or indirectly measuring the potential differences or using sensors which may be of destructive or nondestructive methods. Available software, theoretical, and practical methods for corrosion evaluation and control techniques in reinforced concrete structures were reviewed in this study. Based on the study, it was identified that nondestructive methods supports effectively to access the strength of reinforced concrete structures. Corrosion prediction models supports in lots of saving in aspects such as material, money and time. These instruments aid in predicting the structural strength at different time intervals, and based on the results, repairs can be made to prolong the structural components' useful lives. These software’s tools also follows the concepts evolved from the theoretical methods and the input data provided were arrived from the experimental methods. The accuracy of the software models were compared based on the results obtained from various methods. By these observations, it was concluded that software tools such as Life-365, Thermo-Calc, etc. can be used to forecast the rate of corrosion in structures made of reinforced concrete.

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