Review on Corrosion Simulation and Evaluation Techniques

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Abstract - *Corrosion of steel reinforcement is one of the major problems that affect the durability of concrete structures in marine environment. In practice corrosion of reinforcement is a long-term process. It takes a long time for the initiation and propagation of corrosion. In this paper, it reviews various literature of simulation of corrosion and testing methods. For a research study it is not easy to achieve different degrees of corrosion within a short period of time. Therefore, various methods for accelerating corrosion in concrete structures have been used by several researchers which include exposing the material to more concentrated solution, increasing the wetting period, constant voltage and impressed current techniques. This has been used to study the mechanical behavior of corroded concrete and the bond behavior of corroded re- bars. The corrosion can be tracked using several electrochemical techniques. Most commonly half-cell potential test is used for this purpose. The other methods involve resistivity meter and GPR techniques. Half-cell potential and resistivity meter methods can be used in both field and laboratory environments. Moreover, they can be automated and integrated in to a system for new or existing reinforced concrete structures.*

Key Words: **Corrosion, Reinforced concrete, Reinforcement, Simulation, Evaluation**

1.INTRODUCTION

Reinforced concrete is extensively used for construction on a large scale due to its advantageous structural properties. The corrosion seems to be an all-pervasive event causing extensive obliteration of all types of structures in all countries across the world and has come to be termed as 'cancer' for concrete. As in steel reinforced concrete, the steel is provided to give tensile strength to reinforced cement concrete hence strength of steel is major point of concern. Steel has great affinity towards corrosion which deteriorates not only the steel but the whole RCC structure. The rate of corrosion and corrosion amount depends on various parameters. These parameters are studied by many of the researchers so as to control damage of steel by corrosion.

Though, over passage of time, pH value starts moribund slowly and alkaline neighbouring of the reinforcement bar is lost due to carbonation or access of chloride ions, heralding the corrosion process, which in turn causes cracks and spalling of concrete. Early recognition of the corrosion process could facilitate limit the location and extent of required repairs or replacement, as well as reduce the lost related with remedial work.

2. METHODS OF CORROSION SIMULATION TECHNIQUES

The corrosion of reinforcing steel is generally accelerated by means of various techniques. These techniques help in achieving desired degree of corrosion within a short time span. The various testing methods involve:

(1) Impressed Current Technique
(2) Accelerated Corrosion Test Using Constant Voltage
(3) Accelerated Chloride Migration Test (ACMT)
(4) Alternate Technique

2.1 Impressed Current Technique

An accelerated corrosion test by impressed current technique is a valid method to study the corrosion process of concrete reinforcement. Various researchers used this technique to evaluate the performance of reinforced concrete members. **Shakib et al.** used this technique to accelerate corrosion, in order to find a relation between crack width and level of corrosion [1].

Altoubat et al. studied the effectiveness of this technique to induce corrosion damage in reinforced concrete. In this method, corrosion is induced by applying a constant current from a DC supply to the steel bar embedded in the concrete. The test setup usually consists of DC power source, electrode and electrolyte. The reinforced specimens were subjected to salt contamination before the test by immersing the specimen in 3% NaCl solution. The positive terminal of the DC power source is connected to the steel bars embedded in concrete which act as an anode and negative terminal connected to the counter electrode. With the help of electrolyte (normally NaCl) the current is impressed from counter electrode to rebar through concrete [2].

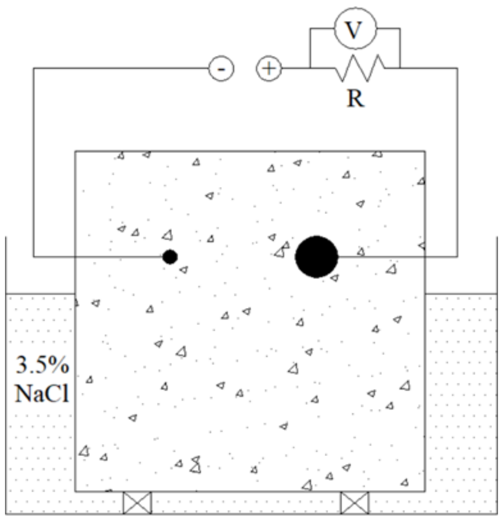

Fig -1: Impressed Current technique - test setup [1]

Shakib et al. performed this test on a specimen of size 250mm*100mm*100mm and found that when a potential difference was applied to the reinforcement different oxides were produced in the presence of oxygen, water and chloride ions, which impart a pressure on the concrete cover and results in cracks. The level of corrosion responsible for surface cracking can be found from the crack width and mass loss [1].

Altoubat et al. from his study on RC columns, concluded that constant current can impart more longitudinal crack than constant voltage [2]. **Shaikh et al.** also studied the effect of this technique by using three different voltages(4V, 6V and 10V) on cylindrical specimen and found that level of voltage applied had no role on the final crack pattern and the decrease in voltage will increase the mass loss up to the appearance of initial surface crack. From these research studies it was clear that impressed current technique can accelerate corrosion within a short time span and thereby also impart visible surface crack on small and large sized specimens [3].

2.2 Accelerated Corrosion Test Using Constant Voltage

An ideal accelerated corrosion simulation technique will help us to produce necessary damage for the reinforced concrete within the required short time span. And it is also used to simulate the exact corrosion pattern that found in the field. So accelerated corrosion test using constant voltage is one of the most effective corrosion simulation technique.

Altoubat et al. used constant voltage test for the simulation of corrosion in reinforced concrete column. He has divided his study into two parts. One is the simulation of corrosion and the other is the testing of specimens after corrosion simulation. For simulation purpose he used accelerated corrosion test using constant voltage. The experiment setup allows the test specimen to corrode to around 8% steel loss. The specimens were cast inverted position such that the bars are penetrated out of the one end of the specimen by 15mm. Stainless steel cathode bars are also in co-operated in the column specimen. The cast specimens were kept in plastic sheets and cured for 28 days by using gunnysacks. After curing, the columns were subjected to one day wetting and 2 ½ days drying by using 3 % NaCl solution. In this test setup, the specimen and 1 Ohm resistor is connected in series with constant voltage power supply which can supply a maximum of 32 volts. The resistor and connections are provided at the top of interface box to data logger to measure output voltage across the specimen and resistor [2].

Based on the study by **Lee et al.** it was found that one day wetting and 2 ½ days dry induces more corrosion damages to specimens. So, this duration is adopted for the wetting and drying cycle [4]. From this study it is clear that accelerated corrosion test using constant voltage is an effective method to increase the rate of corrosion within a short period of span.

2.3 Accelerated Chloride Migration Test

Accelerated chloride migration test (ACMT) is one of the most common method to study the corrosion process of concrete reinforcement. **Bhalgamiya et al.** used ACMT for evaluating migration coefficient, which can be used for accelerating reinforcement corrosion. The simulation technique is also used to accelerate chloride ion migration in cement-based material to estimate its permeability. The test specimen for this setup was made by placing rebar centrally in a 75mm*150mm concrete cylinder. The test setup consists of two acrylic cells. The test set up is illustrated in figure 2.

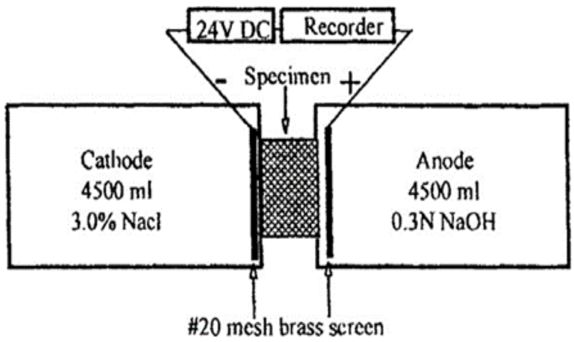

Fig -2: Accelerated chloride migration test setup [5]

The anode cell was filled with 0.3% mol/l of NaOH solution and cathode cell was filled with 3% NaCl solution. The cells are connected in to a 24V DC power source. The mesh electrodes were placed on the end of the specimen in such a way that the electric field is applied across 50 mm thick concrete slice. A data logger is used in this setup in order to measure the current. The chloride ions will be transported through concrete sample under an applied voltage. The quantity of chloride ions present in anode and cathode cells are measured periodically. Thus, the corrosion can be simulated by the passage of chloride ions through the concrete sample [5].

2.4 Alternate Technique

Alternate technique using artificial climate environment was used to study the corrosion process of concrete reinforcement. For this method, **Yuan et al.** proposed an artificial climate room which is maintained for this method. **Yuan et al.** proposed an artificial climate room which was maintained at a high temperature of 40-degree Celsius, high relative humidity of 80 % on the room is controlled by computer system. The reinforced concrete beam is kept in this artificial room and the specimen undergoes repeated wetting and drying. It is done by spraying 50 % NaCl for about 1 hour and an infrared light is passed through it for 7 hours. The reinforcement corrosion is observed. It was found that the characteristics of steel in artificial environment is same as the properties that steel exhibited under natural environment [6].

3. METHODS OF CORROSION EVALUATION TECHNIQUES

Corrosion is a chemical process and not too easy to evaluate the magnitude and damage given to the steel of reinforced concrete structure. Several techniques have been reported in various researches that can be used for monitoring and assessing the corrosion of rebars in concrete structures for diagnosing the effects and cause of corrosion. The various evaluation methods involve:

- Half Cell Potential
- Resistivity Method
- Ground Penetrating Radar (GPR)
- Ultrasonic Guided Wave Technique

3.1 Half Cell Potential

Half-cell potential test is a commonly used technique for assessing the severity of corrosion activity in concrete structures. **Flis et al.** , **Grantham et al.** and **Zvica** extensively described the use of half-cell potential measurement for determining the probability of corrosion [7],[8],[9]. The rate of corrosion is evaluated by measuring the potential difference between a standard reference electrode. Normally $Cu/CuSo_4$ reference electrode placed on the surface of concrete with the steel reinforcement underneath. The concrete surface is wetted by spraying water over the testing location before measurement. The connecting lead terminal from the negative terminal of volt meter is connected to the reference electrode and positive terminal to the projected bar. The voltmeter measure direct current voltage and has the capacity to be battery operated. Which is illustrated in figure 3 [10].

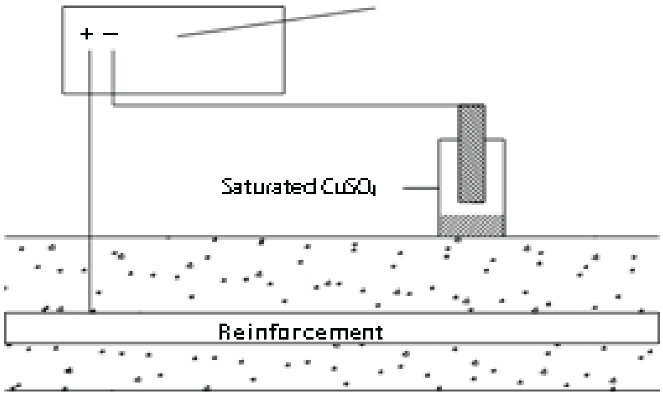

Fig -3: Half-cell potential measurement [10]

It should have a varying input impedance ranging from 10 to 200mOhm. From various researches, they examined that when the half-cell potential measurement is more than -350mV, chance of having active corrosion is more than 90%. The chance of corrosion is less than 10%, if the measured potential value is more positive than -200mV. For a potential value in between -200mV and -350mV, there is uncertainty in interpreting the test results. From these various studies, it is noted that, half-cell potential technique is an effective and most popular method of in situ corrosion testing. But one of the major drawbacks of the method is that, it merely provides information about probability of corrosion and not about the rate of corrosion.

3.2 Resistivity Method

The probability of corrosion in concrete structures can also be determined by measuring the concrete resistivity. Corrosion of concrete structures mainly depend on the ionic conductivity of concrete. Various research studies proved that electrical resistivity of concrete is an effective parameter to evaluate the probability of corrosion in RC structures. **Feliu et al.** showed that concrete resistivity and corrosion rates are inversely related [11].

Sadowski observed the corrosion rate in a concrete slab (200*750*750mm) by using the combination of half-cell potential and concrete resistivity measurements and they found that these two non-destructive techniques are more effective to give the maximum information regarding the probability of corrosion in concrete structures. An equipment called resistivity meter was placed on the concrete surface in order to measure its resistivity.

Concrete resistivity is a good indication of probability of corrosion. When the electric resistance is lower, more corrosion current will flow through the concrete and thus the probability of corrosion is greater. The test setup is shown in figure 4 [10].

Fig -4: Concrete resistivity measurement – test setup [10]

Probability of corrosion with respect to concrete resistivity suggested by **Elkey et al.** is as shown in table 1. Because of its simplicity and reliability, many researchers proposed this method as an effective measurement technique to monitor rebar corrosion in concrete structures [12].

Table -1: Dependence between concrete resistivity and corrosion probability [10]

Concrete resistivity ⍰, kΩcm	Probability of corrosion
⍰ < 5	Very high
5 < ⍰ < 10	High
10 < ⍰ < 20	Low to moderate
⍰ > 20	Low

3.3 Ground Penetrating Radar

Ground penetrating radar, an alternative non-destructive testing (NDT) method, has become a valuable tool for detection of reinforcement corrosion in concrete structures. **Zaki et al.** examined that, GPR is an electromagnetic (EM) investigative method, widely used in the reflection mode. In this technique, a signal is emitted via an antenna into the structure under investigation. From this research it showed that the principle of non-destructive testing by GPR involve the transmission of EM waves into structure. The velocity of propagation of signal is reduced initially due to the existence of high-water content, when the EM wave are allowed to propagate through the corroded concrete structure. The propagation of electromagnetic waves and permittivity depend on dielectric properties and EM properties of the material respectively [13].

Whenever EM waves encounter an interface of two media having dielectric constants, part of the wave is reflected back to the receiving antenna. A receiving antenna recorded the reflected waves. And these received waves were then converted into voltage wave called single trace (a scan) as shown in figure. By investigating a material along a line, GPR system generate rapid succession of trace called radar gram (b-scan) as shown in figure 5 [13].

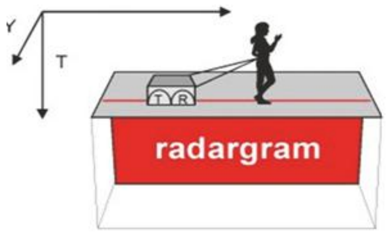

Fig -5: Radargram (*b*-scan) [13]

Hasan et al. conducted an investigation to find out the relationship between the amount of corrosion in reinforced concrete and GPR maximum positive amplitude. By impressing direct current into the steel bars, accelerated corrosion was simulated in the lab within a short period of span. And thus, with the different levels of mass loss ranging from 0 to 45%, the rate of corrosion was varied in the rebars. These corroded rebars were placed into three different oil emulsion tanks having different dielectric properties similar to concrete and then recorded the maximum amplitude from the corroded rebars by using GPR technique [14].

S Hong et al. proposed a new method for evaluating the reinforcement concrete structure with GPR. They used a new signal processing method for normalizing the intensity of GPR image. These processed images were used to compare and find out the changes in the GPR detection due to corrosion [15].

3.4 Ultrasonic Guided Wave Technique

Ultrasonic guided (UG) wave technique detects the presence of steel corrosion in concrete structures based on the propagation of UG waves. Investigations based on UG wave technique have been proved that these waves are more sensitive to damages due to corrosion and can be used to detect the corrosion even at their early stage.

Liu et al. carried out studies on a mortar specimen (150mm*150mm*40mm) with 10 mm diameter steel bar at the center to predict the degree of corrosion by utilizing this technique. Piezoelectric sensors were used to generate and receive ultrasonic waves and was recorded by an oscilloscope. The data is recorded until the cracks appeared on the specimen, and the degree of corrosion was determined based on the trend of amplitude of these signals. The amplitude of attenuation has a good correlation with the damage due to corrosion. The diagram of test set up is shown in figure 6 [16].

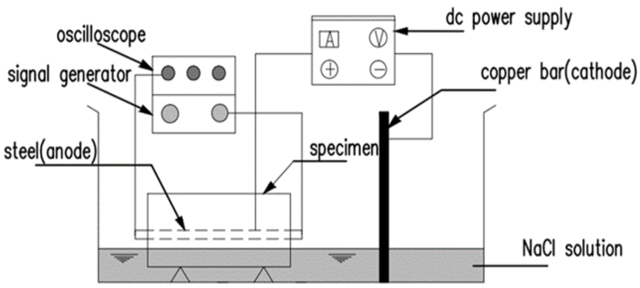

Fig -6: The diagram of ultrasonic guided wave monitoring system [16]

Li et al. Also utilized this technique on a concrete specimen of size 500mm * 120mm * 150mm and analyzed the UG wave dispersion curve. Based on the analysis it was found that as the corrosion damage increase, the relative variation for first wave peak increase initially and then decreases [17].

It was reported that the ultrasonic guide has the capability to propagate long distance and has high sensitivity and broad coverage (**Liu et al., Mukherjee et al., Li et al.)** [18]. Because of the above-mentioned properties, this technique is proposed by many researchers to identify the exact location, size, shape and nature of concrete damage caused by corrosion. Hence this technique dominates over other traditional methods.

4. CONCLUSIONS

The control of corrosion in steel reinforcement is necessary to prevent damage and failure of concrete structures. There are various methods by which corrosion control of reinforcement can be achieved which includes the use of:

- Corrosion inhibitors
- Alternative reinforcements such as cement polymer composite coated rebars, basalt rebars and corrosion resistant steel deformed rebars
- Steel and concrete coating
- Electrochemical techniques

Failure of concrete structures due to corrosion of embedded rebars is a major problem causing significant loss of time and money. An effective method to measure corrosion is a fundamental requirement for planning maintenance, repairing and removal of reinforced concrete structures. The content of this paper will be helpful for researchers to simulate corrosion and to select the suitable corrosion testing method.
This paper provides the overview on some commonly used corrosion simulation and evaluation techniques in reinforced concrete structures. In result of study of various papers, it is observed that, the rate of corrosion can be increased by using accelerated corrosion test within a short period of span. And also, the presence of rebar corrosion in concrete structures can be effectively assessed by using suitable evaluation technique.

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