

CORROSION OF REINFORCED CONCRETE: A REVIEW

AMRITA RANI NAYAK¹, Dr. MANJU DOMINIC²

¹PG Student (Structural Engineering), Galgotias University, Gr. Noida (U.P.),

²Professor, Dept. of Civil Engineering, RIET, Nagaroor, Trivandrum (Kerala)

ABSTRACT: The strength of reinforcement is much more than concrete, and also concrete is the widely used engineering material; These are the three main reasons for its wide use:- The first and foremost reason is the opposition of concrete to water, which is way more than wood, steel used for structural purposes. Secondly, the concrete can be easily casted or moulded into different structural sizes and shapes. The most chief reason behind the popularity of concrete is that it is readily available easily and cost efficient i.e. economical. The concrete is provided with steel reinforcement so as to toughen the structural element in tension as because concrete is weak in tension, but structures do fail reason is the corrosion attack on steel reinforcement. The main reason for degradation or deterioration of any structure is the corrosion attack on the reinforced bars in reinforced concrete structures like tall buildings, bridge deck, tunnels, dams, etc. Basically, corrosion is defined as the process that occurs naturally when the reinforced concrete structures within which the steel reinforced bars are embedded starts rusting. In other terms we can say that, corrosion of reinforced concrete is the damage of metal (i.e. steel reinforcement) by the chemical, electrochemical, and electrolytic reactions within the concrete surface. Deterioration and the damage which is caused by corrosion reduces the durability, resilience, strength, stability and safety ratio or the safety margin of concrete structures, which will cause serious structural failure, and then eventually it will require a huge amount of money in renovating these structures. The present work deals with a review on corrosion rate happening during the life of reinforced concrete structures. It also focuses on different aspects of corrosion of reinforced concrete.

Keywords:- Corrosion, Reinforced concrete, Corrosion rate, Precautions from corrosion, Maintenance and Repair

1. INTRODUCTION

Corrosion of reinforcement in concrete structures has been considered as the key reason causing extensive damage, deterioration and degradation of reinforced concrete structures globally, specifically corrosion affects the structures situated in the coastal and marine locations. The most important cause of corrosion in reinforcing steel are the way in of chloride ions and carbon dioxide into the concrete structures to the steel surfaces in it, in the presence of air [2].

There are mainly three stages of the deterioration process:-

1. Initiation: In this period, the rate of corrosion is very slow in spite of the entrance of hostile species into the reinforcing steel from the environment.
2. De-passivation: This step happens when the circumstances essential for the beginning of corrosion is fulfilled, and hence the movement of hostile species through concrete cover has started. This de-passivation is either due to the chloride presence or the carbonation phenomenon.
3. Propagation: The corrosion of reinforced concrete causes considerable loss of elemental metal bars. Corrosion results in the palling out of the concrete cover and micro cracking caused internally. These are caused as a result of the high tensile stresses which are produced by the expansion in the volume of the corroded products.[3]

1.1 What is this corrosion of reinforced concrete? As I have mentioned above; Corrosion is defined as the process that occurs naturally when the reinforced concrete structures within which the steel reinforced bars are embedded starts rusting. In other terms we can say that, [2] corrosion of reinforced concrete is the damage of metal (i.e. steel reinforcement) by the chemical, electrochemical, and electrolytic reactions within the concrete surface environment. It forms as the concrete ages.

1.2 How does corrosion of reinforced concrete occur? Corrosion is initiated when conditions that are favorable or essential for corrosion of steel reinforcements, such as CO₂ and chloride from different salt solutions, start to go into the concrete and reach the steel reinforcement. As in an electrochemical reaction, electrons do move from the anodic zone to the cathodic zone, which leads to generation of ferrous ions at the anode and hydroxide ions at the cathode. Eventually, this will lead to a potential difference between the anodic and cathodic areas of the steel reinforcement at the surface [2]. Hence, it will result in a byproduct known as rust. However, these rust takes up a large volume around the steel and which eventually exerts an internal pressure hence, causes the surrounding concrete to crack and damage the concrete. These cracks on exertion of more pressure causes way towards the surface of the concrete, causing even more CO₂ and

chloride to break into the concrete and speeding up the process of corrosion. Almost 90% of damage to reinforced concrete structures is caused due to corrosion.

1.3 Classification of Corrosion:-Corrosion occurs in many ways and it can be classified based on one of these following three factors:- [2]

- *Nature of the corrodent:* Under this classification, the corrosion maybe "wet" or "dry". In wet corrosion, the most essential is the presence of moisture and in the later type of corrosion, it involves the reaction with gases at high temperatures.
- *Mechanism of corrosion:* In this criteria, corrosion may occur either 'electrochemically' or with 'direct' chemical reactions.
- *Appearance of the corroded metal:* Under this classification, corrosion can be classified as either 'uniform' or 'localized'. If the metal corrodes at an identical rate over the total surface it is the uniform corrosion and when only small areas get affect edit is the localized corrosion.

2. CORROSION OF REINFORCED CONCRETE

2.1 CORROSION MECHANISM IN REINFORCED CONCRETE:

Reinforced concrete corrosion is influenced by the production of the electrochemical potentials in the following ways:-

1. When there is difference in metals which are present in the concrete like steel rebars, aluminium conduit pipes, then there occurs the formation of concentration cell.

2. Concentration cells may also be formed near reinforcing steel by the differences in the concentration of dissolved ions (at cathode & at anode), such as alkalis and chlorides. (Figure2)

The following reactions occur at anode and cathode [5].

Anode: $Fe \rightarrow Fe^{2+} + 2e^-$ (Metallic iron)

$FeO.(H_2O)_x$ (Rust)

Cathode: $O_2 + H_2O + 2e^- \rightarrow 2OH^-$

Some factors which are essential to initiate the corrosion process are the presence of humidity and oxygen; without these two factors corrosion is not possible [6, 7, 8]. If the amount of water or oxygen is limited then the rate of corrosion is slow. Presence of moisture and oxygen acts as catalyst for corrosion to occur, as they helps in forming OH-

ions more; henceforth producing rust components even more.

Fe (OH)- [4,8].

Following reactions (Eq1. to 3.) represent the formation of the rust after the iron dissolution occurs at the anodic sites in the reinforcement:- [6]

$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$ (Ferrous Hydroxide) (1)

$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$ (Ferric Hydroxide) (2)

$2Fe(OH)_3 \rightarrow 2H_2O + Fe_2O_3 \cdot H_2O$ (Rust) (3)

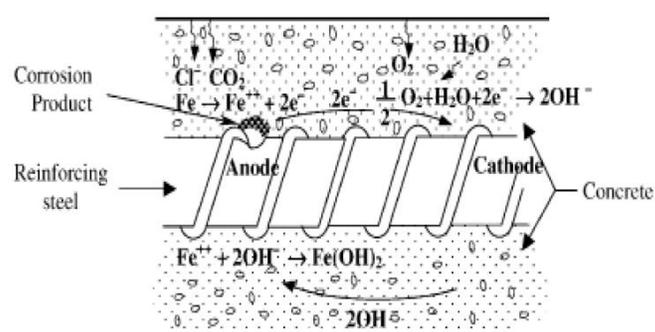


FIG 1- A Simplified Model for Electrochemical process of corrosion of steel in concrete [6]

Anode & Cathode in Corrosion of Reinforced Concrete:

Corrosion process of steel concrete is mainly associated with degree of electro-chemical method. When there is dissimilarity in electrical potential of the reinforcement in concrete, associated concentration cell is set up. For the electrochemical process, within the steel one half becomes the anode (an electrode with a positive charge) and another half becomes the cathode (an electrode with a negative charge) and connected by the electrolyte in the form of pore water, which is present in the cement paste (hardened). The element ions Fe^{2+} which is positively charged pass into electrolyte solution at the anode, whereas the negatively charged free electrons pass into the electrolyte solution at cathode, here they are absorbed by the constituents of the solution and mix with water and oxygen to generate hydroxide ions (OH-).

2.2 CHLORINE INDUCED CORROSION:

The main reason behind the corrosion of steel in reinforced concrete is the chlorine attack [9, 10]. The major source of chloride ions is the de-icing salts or the seawater [12, 13]. Cement, water, aggregate and also admixtures can also facilitate chloride in concrete. Chlorides enters into the concrete through the pore

network and micro cracks, forming the oxide film over the reinforcing steel and hence, speed up the reaction of corrosion and concrete deterioration [15, 16, 17]. The passivity of steel is broken when a required quantity of chlorides is present in the pore solution. The passivity of steel also depends upon the OH⁻ concentration in the pore solution. Some author shows that the passivity is broken when the ratio of Cl⁻ concentration to OH⁻ concentration exceeds a particular value [10]. The mechanism of reinforcement corrosion in concrete due to chloride attack is an electrochemical process by which the passivating layer of steel is lost by means of formation of micro cells on the surface of steel by chloride ions. The moisture present in the pores of concrete acts as an electrolyte and the area adjacent to the concentration of chloride ions becomes cathode, thus starting the electrochemical process [13]. The Bureau of Indian Standard specified the maximum chloride content in cement to 0.1 percent [14].

The CTL can be defined as the maximum chloride content at the depth of steel required to sustain local passive film breakdown which promotes the corrosion process [5]. It is usually presented as the ratio of Cl⁻ to OH⁻ [10]. Chlorides present in two forms in the concrete, namely bound chloride and free chloride. In bound chloride, chemically bound chlorides are used in the hydration product of cement and physically bound chlorides are absorbed on the surface of the gel pores. This is important as only the free chlorides are relevant to the corrosion of reinforcement. M.A.Quraishi et al. [5], defined the chloride threshold level as the chloride ion concentration of steel bars in concrete provided that there are no damages at the rebar concrete interface as shown in Table 1[9,11] (Figure 3).

Sl. No.	Risk of corrosion Chloride Content (% wt. of cement)
1.	Negligible 0.4
2.	Possible 0.4 – 1.0
3.	Probable 1.0 – 2.0
4.	Certain >2.0

Table 1 Corrosion risk classification at different chloride levels. [1]

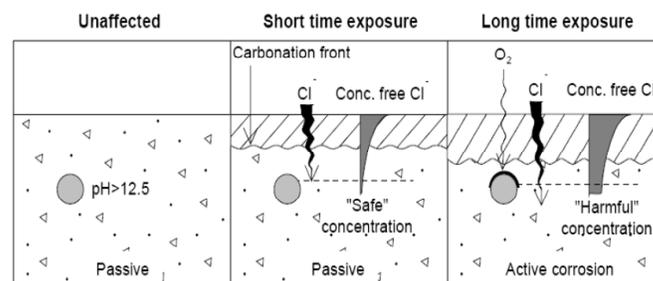


FIG 2- Corrosion by chloride ions and carbonation. [1]

3. CAUSES OF CORROSION IN REINFORCED CONCRETE

Metal corrodes once it reacts with another substance such as oxygen, hydrogen, any electrical current or also even dirt and microorganisms. Corrosion can also occur when metals like steel are placed under excess stress causing the material to crack. In reinforced concrete construction, the corrosion of reinforcement takes place due to the presence of chlorides and sulphates beyond a permissible limit and even when sufficient alkalis is not obtained within the concrete to maintain steel in a positive condition.

It can be noted that no corrosion takes place if the concrete is dry, i.e., probably below relative humidity of 60%, it is because enough water is not there to promote corrosion [27]. It can also be noted that corrosion does not take place, if concrete is fully immersed in water, because diffusion of oxygen does not take place into the concrete [27]. So, probably the optimum relative humidity for corrosion is 70-80% [27]. The products of corrosion occupy a volume as much as 6 times the original volume of steel, depending upon the oxidation state [15].

Increase the oxygen content has 2 effects:

- (i) It forces the cathodic reaction to the right, producing more OH⁻ ions [27]
- (ii) It removes more electrons and therefore, accelerates the corrosion at the anode. [27]

The corrosion occurs at the entire anode, and the rust forms at the cathode.

4. FACTORS INFLUENCING CORROSION OF REINFORCED CONCRETE

4.1 QUALITY OF CONCRETE: Concrete comprises of cement, water, coarse aggregate (gravel, pebbles) and fine aggregate (sand). The right quality of materials with proper w/c ratio, proportionate mixing, adequate compaction by tamping or vibration and proper curing results in good quality of concrete. If any of the above steps

are not done in a correct manner, then that will result in a bad quality concrete and there is a chance of corrosion of reinforcement. High strength concrete, i.e. dense concrete is impervious to a large degree and generally resists the corrosion of embedded steel [10].

4.2 COVER THICKNESS OF CONCRETE REINFORCEMENT:

The reinforcement is protected from the surrounding exposure by providing suitable concrete covering over it. The more the cover thickness, more is the degree of protection against the various climatic and other environmental conditions. For different structural members, the cover thickness should be different, it depends upon their importance and degree of exposure. Consistency of thickness of concrete cover over the reinforcement is also very crucial for its corrosion protection.

4.3 CONDITION OF REINFORCEMENT: If the reinforcement is contaminated with salt or corrosion has begun, then the corrosive action on reinforcement after placement of concrete is promoted rapidly. The surface condition of the steel reinforcement, at the time of placing of concrete, affects the corrosion rate of steel reinforcement.

4.4 EFFECT OF CHEMICALS: Chemicals either from environment or from within the concrete are the main source for the deterioration process. Due to the attack of chemicals, the concrete starts cracking, which is the first sign of deterioration. The chemicals are mainly due to presence of salt, carbonation, chloride attack and reaction of sulphates with tricalcium aluminate (C3A) which are present in cement. Concrete is an intimate mixture of cement, aggregate and water which in the green state is highly alkaline [10]. In such alkaline conditions, the reinforcements are covered with a film of oxide which protects the steel.

4.5 POROSITY OF CONCRETE: The penetration of aggressive chemicals into the concrete is possible due to permeability or porosity of concrete. The porosity of concrete depends upon factors, such as [10]:-

- Size, distribution and continuity of capillary pores of concrete
- Water-cement ratio for degree of hydration of concrete
- Age of concrete
- Degree of compactness
- The size and grading of aggregate
- Type of cement

4.6 EFFECT OF HIGH THERMAL STRESS: Normal concrete can withstand temperature upto 100°C [10]. Beyond this temperature the deterioration or degradation of concrete starts. The concrete used in industrial plants and power stations require special protective measures or else the concrete may develop thermal cracks. Cracked concrete structures are eventually affected by the environmental chemical and hence the process of corrosion starts.

4.7 FREEZING AND THAWING CONDITION: In cold regions, the moisture in the pores of concrete freezes. The formation of ice gives rise to volumetric expansion, which may increase internal pressure of surrounding concrete mass. The consequences are development of cracks in concrete and eventually leads to corrosion of reinforcement.

5. EFFECTS OF CORROSION IN REINFORCED CONCRETE

Corrosion affects both directly and indirectly to our daily life. We can easily identify corrosion on metal furniture, grills, automobile parts, metal doors, window panels and other household tools made up of metals and alloys. Corrosion can cause much more severe consequences to human lives when an electric tower collapsed due to corrosion of steel metal, damage of buildings or collapsing of the bridge due to the corrosion of the steel reinforcing bar in concrete, etc. The major consequences of corrosion can be represented in three ways:

- It is extremely expensive
- It is a waste of natural resources
- It causes inconveniences and damages to human beings and even loss of life

Corrosion results in a tremendous economic loss of infrastructures and it slows down the economic growth of countries. [18]

The main consequences of reinforcement corrosion are:-

1. decrease in the steel cross-section
2. possible loss of steel ductility
3. cracking of the concrete cover
4. loss of the steel concrete bond. [26]

5.1 MAJOR ECONOMIC AND SOCIAL CONSEQUENCES OF CORROSION ARE:-

- Replacements of corroded equipments and materials
- Aesthetic appearance of materials is very important since corroded surfaces are unpleasant to the eye of the observer. Hence, equipments and structures are required to be painted to improve its appearance

- Shutdown of plants and equipments due to corrosion failure. Because of unexpected corrosion failures different industrial plants like electrical, chemical, nuclear power plants, etc. are shut down
- Loss and contamination of valuable products
- Damage of equipments due to corrosion failures
- Serious damage to the liability of structures
- Safety and health of the public, for example, sudden failure of plants can cause an explosion, release of toxic gases, fire, and acids and other hazardous and flammable materials are released which cause loss of diversity, people, etc.
- Depletion of natural resources, including metals and the fuels, which are used to manufacture them.

Our country India loses a staggering amount of Rs2 lakh crore per year due to corrosion and related issues [29]. Corrosion is causing a huge amount of financial damage to economies, wasting a vast amount of natural resources and finances.

The annual worldwide cost of metallic corrosion is estimated to be over \$2 trillion, yet experts believe 25 - 30% could be prevented with appropriate corrosion protection [29]. Improperly planned construction projects can lead to a corroded structure needing to be repaired or sometimes it is replaced, hence it is a waste of natural resources and contradictory it is a global concern over sustainability. In addition, corrosion can lead to loss of life, concern on safety, additional indirect costs and damage to the infrastructure.

5.2 CORROSION EVALUATION:-

The calculation of efficiency of inhibitor can be done from the weight loss (i.e., reduction in corrosion) by using the given formula [1]:-

$$\text{Weight loss (\%)} = [(W_1 - W_2) / W_1] \times 100$$

where, W_1 = Initial weight of rebar

W_2 = Weight rebar after removal of corrosion products

6. RESIDUAL STRENGTH OF CORROSION DAMAGED STRUCTURES

In a study, an attempt has been made to predict the residual strength (flexural) of a corroded beam, by the use of conventional flexural formula, which takes into account the loss of metal due to corrosion and a correction factor is applied to account for the loss of bond. The correction factor is a function of corrosion current density, corrosion time, and the reinforcing bar diameter [19]. The

development of a new, simplified criterion, known as PCORRC, for prediction of the remaining strength of corrosion defects in moderate- to high-toughness pipeline steels that fail by plastic collapse [19].

The complete expression for the *PCORRC for Pipeline Corrosion Criterion* is then given by [20]:

$$\sigma_u \frac{2t}{D} \left(1 - \frac{d}{t} \left(1 - \exp \left(-0.157 \frac{L}{\sqrt{Rt}} \right) \right) \right)^{P_d} =$$

The results of above equation, which is performed under the sponsorship of PRC, on development of a simplified criterion for the predicting remaining strength of corrosion defects under internal pressure with minimal excess conservatism [20]. The value of PCORRC is demonstrated in comparisons that show it is capable of reducing excess conservatism significantly in the class of defects that fail by plastic collapse, potentially resulting in significant reductions in pipeline maintenance and repair costs [20]. The investigation shows that the first priority for future work is the development of a comprehensive definition for the lower bound for the plastic collapse failure of corrosion defects [20]. PCORRC has the potential to simplify defect assessment and also to reduce the number of unnecessary cutouts and repairs.

7. CORROSION RATE IN CORROSION OF REINFORCED CONCRETE

The safety and serviceability of the structure are affected. The rate of the general deterioration is a function of the corrosion rate, defined as the amount of metal oxidized by unit of metallic surface over a certain period of time [27]. There is a requirement of using non-destructive techniques, by which we are able to measure the corrosion rate in order [27]:-

1. To detect the steel depassivation;
2. To predict the residual life of the structure when actively corroding; and
3. To monitor the efficiency of repair systems.

Maintenance, planning of the restoration and more recently residual service life calculations of these structures need rapid, non-destructive inspection techniques able to detect corrosion of the rebars at an early stage, to define adequately which areas of structures require repair and provide a quantitative measure of the corrosion rate [21].

For *measurement of the corrosion rate* of reinforcing steel in concrete, many electrochemical and non-

destructive techniques are available for monitoring corrosion of steel in concrete structures such as [21]:-

1. Open circuit potential (OCP) measurements
2. Surface potential (SP) measurements
3. Concrete resistivity measurement
4. Linear polarization resistance (LPR) measurement
5. Tafel extrapolation
6. Galvanostatic pulse transient method
7. Electrochemical impedance spectroscopy (EIS)
8. Harmonic analysis
9. Noise Analysis
10. Embeddable corrosion monitoring sensor and
11. Cover thickness measurements
12. Ultrasonic pulse velocity technique
13. X-ray, Gamma radiography measurement
14. Infrared thermograph Electrochemical
15. Visual inspection

7.1. Open Circuit Potential (OCP) Measurements: The tendency of any metal to react with an environment is specified by the potential it develops in contact with the environment. In reinforced concrete structures, concrete acts, as an electrolyte and the reinforcement will develop a potential depending on the concrete environment. The principle of this technique is essentially measurement of corrosion potential of rebar with respect to a standard reference electrode, such as saturated calomel electrode (SCE), copper/copper sulfate electrode (CSE), silver/ silver chloride electrode etc. [21].

(mV vs. SCE)	mV vs. CSE	Corrosion condition
< -426	< -500	Severe corrosion
< -276	< -350	High (<90% risk of corrosion)
-126 to -275	-350 to -200	Intermediate corrosion risk
> -125	> -200	Low(10% risk of corrosion)

Table 2: Corrosion condition related with half-cell potential (HCP) measurements [31]

The recognition, diagnosis and capacity of corrosion in concrete structures are essential. Various techniques for

detecting and measuring corrosion will provide data on the causes, detection or rate of corrosion [32]. The main methodology of detection of corrosion is the half-cell potential (HCP) measurements. The corrosion method of steel in concrete can be followed using several electrochemical techniques.

7.2. Linear polarization resistance (LPR) measurements:

The LPR technique has become a well-established method of determining the instantaneous corrosion rate measurement of reinforcing steel in concrete [33-36]. The technique is rapid and non-intrusive, requiring only localized damage to the concrete cover to enable an electrical connection to be made to the reinforcing steel [35]. Due to the widely spread corrosion of reinforcing steel in concrete structures there has been a demand for the development of non-destructive techniques to enable accurate assessment of the condition of reinforced concrete structures. LPR monitoring technique is rapid and non-intrusive, requiring solely the affiliation to the reinforcing steel. The data provides a valuable insight into the instantaneous corrosion rate of the steel reinforcement, giving more detailed information than a simple potential survey [34]. The LPR information allows a additional careful assessment of the structural condition and could be a major tool decide upon the optimum remedial strategy to be adopted. It's so imperative that the LPR measurements obtained are correct.

8. TYPES OF CORROSION IN REINFORCED CONCRETE

The following are the types of corrosion that takes place in reinforced concrete structures [29]:-

8.1 Uniform Corrosion: This is the most common form of corrosion, it usually takes place consistently over most areas of the material's surface.

8.2 Pitting Corrosion: It is one of the most aggressive forms of corrosion. Pitting is hard to characterize, predict, or detect. It is a localized type of corrosion, and it happens when a local anodic or cathodic point forms a corrosion cell with the environmental surrounding surface. This pit create a hole or cavity, which helps for penetration of the material in a vertical downward direction from the surface. Pitting corrosion can be caused by damage or a break in the oxide film or a protective coating and it also can be caused through non-uniformities in the structure of the metal [2]. It causes a structure to fail despite a relatively low loss of metal.

8.3 Crevice Corrosion: This form of corrosion occurs in areas where oxygen is restricted such as under washers or bolt heads. This localized corrosion usually results from a

difference in the ion concentration between two areas of metal. The stagnant microenvironment prevents circulation of oxygen, which stops re-passivation and hence causes a build-up of stagnant solution moving the pH balance away from neutral. The imbalance between the crevice and the rest of the material contributes to the high rates of corrosion. Crevice corrosion can be minimized by proper joint design.

8.4 Intergranular Corrosion: This form of corrosion occurs when impurities are present at the grain boundaries which is formed during solidification of an alloy. It can also be caused by the enhancement or depletion of an alloying element at the grain boundaries. This type of corrosion occurs along or adjacent to the grains, affecting the mechanical properties of the metal despite of the entire material being unaffected.

8.5 Stress Corrosion Cracking (SCC): Stress corrosion cracking can be defined as the growth of cracks because of a corrosive environment, which can lead to the failure of ductile metals when it is subjected to tensile stress, particularly at high temperature. This type of corrosion are more common among alloys than with pure metals.

8.6 Galvanic Corrosion: The galvanic corrosion occurs when two different metals with physical or electrical contact are immersed in a common electrolyte (such as salt water). It can also occur when a metal is opened to different concentrations of electrolyte. Where two metals are submerged together, known as a galvanic couple; the more active metal (the anode) corrodes fast than the less active metal (the cathode). There is a galvanic series, which determines metals corroding faster. This series is useful while using a sacrificial anode to protect a structure from corrosion [2].

9. EFFECTS OF CORROSION ON OFFSHORE STRUCTURES

Seawater is a corrosive environment that affects infrastructure, particularly in polluted seawater [23]. Structures like dams, bridges, light houses, etc. are subjected to this environment and operate in a harsh environment. Allowance must be made for structural deterioration since protective measures such as paint coatings, galvanizing or cathodic protection may be ineffective [30]. For offshore structures, the main factor is the deterioration or degradation of structural strength and structural integrity in assets management. There are many approaches made for asset management like estimating the probability of safety within a given remaining life or estimation of remaining life for a given level of performance. These matters are influenced by

- the loss of structural integrity by pitting corrosion

- the loss of section thickness for structural elements
- wear and tear of the metal surfaces in the water bodies
- affects the strength and durability of the structures
- decaying of the metal surfaces, visibility of cracks
- for marine structures, there is loss of wall thickness
- failure of the structures, leading to loss of life & people, also it affects economically

10. CORROSION PRECAUTIONS/ PREVENTION METHODS

Corrosion control is usually handled in design codes in the form of minimum concrete cover, minimum grade of concrete, maximum allowable crack width, etc., when exposure conditions are particularly harsh, there is a need to apply special measures beyond the minimum provided in the design codes [1]. The corrosion control methods are divided into 2 types; Active measures and Passive measures. The passive measures is to the improve the durability of concrete, which includes the use of high quality concretes produced by the amalgamation of various chemical admixtures (e.g. plasticizers, superplasticizers, shrinkage reducing admixture corrosion inhibitors) and mineral admixtures. On the other hand, the active measures directly reduces the corrosion rate, which include cathodic protection and galvanization. Some of the widely used methods and strategies to control corrosion are as follows:-

10.1 Corrosion Inhibitors

A corrosion inhibitor is an admixture that is used with the concrete to prevent the metal, embedded in it from corroding. There exists various types of inhibitors available (corrosion inhibiting materials), the most wide used admixture is basic on calcium nitric. It is added to the concrete during the mixing of concrete, the nitrite ions present in the corrosion inhibiting admixture will oxidize the ferrous oxide. However, the passivating layer also contains some ferrous oxide, which when the chloride ions reach the steel, can initiate corrosion and also the nitrite ions present in the corrosion inhibiting admixture will oxidize the ferrous oxide [2].

Calcium nitrite corrosion inhibitor usually comes in a liquid form, containing about 30% calcium nitrite solids by weight.

10.2 Coatings of steel

The objective of coatings on steel bar is to provide a durable barrier to the reactive materials, like chlorides. The coatings should be strong to withstand pouring of

concrete and compaction by vibration of vibrating machine. The cement slurry coating is a cheap method for temporary protection of reinforcement against rusting, when kept in storage.

Central electro chemical Research institute (CECRI), Karaikudi, have suggested a method for prevention of corrosion in steel reinforcement in concrete [2]. The steps involved are as follows:-

10.2.1 Derusting

The reinforcement are cleaned with a de rusting solution, then without delay rods are leaned, with wet waste cloth and cleaning powder. The rods are then rinsed in water and kept to dry.

10.2.2 Phosphating

The Phosphate jelly is then applied to the bars, with a brush. This jelly is kept for about 45-60 minutes, and then removed by a wet cloth, then an inhibitor solution is brushed over the phosphated surface.

10.2.3 Cement Coating

Slurry is prepared by mixing the inhibitor solution and Ordinary Portland cement and is applied on the steel bar.

10.2.4 Sealing

A sealing solution, having an insite curing effect is brushed after the rods are air cured. Again a second coat of slurry is applied and then the bars are air dried. Two coats of sealing solution are applied to the bars, in order to seal the micro-pores of the cement coat so as to make it impermeable to corrosive materials.

Epoxy Coatings: It is one of the effective methods of steel bars coating. Firstly, the steel bars are blasted to remove all mill scale and give a surface finish to it. This helps and ensures a good bond between epoxy and steel. The bar is then heated to a controlled temperature. Electrostatically charged epoxy powder particulars are deposited evenly on the surface of the bar [3]. The coating thickness vary from 130 to 100 microns, it usually looks greenish in color. Epoxy coated bars have an excellent protection to corrosion in harsh environment, also there are a few limitations of epoxy coated bars:- (i.) Cutting and bending may injure the steel, after the epoxy coating treatment.

(ii.) The bars cannot be welded.

(iii.) The epoxy is not resistant to rays of sun. The bars should not be exposed to sun for long duration before use.

(iv.) The coating may get damage during vibration of concrete.

(v.) The treatment is very costly, as that of steel.

10.3 Galvanized Reinforcement

This Galvanizing of reinforcement process consists of dipping the steel bars in molten zinc, which results in a coating of zinc, bonded to the surface of steel. The zinc coating form a passive layer and avoids corrosion.

10.4 Cathodic & Anodic protection

Cathodic protection is an electrochemical way of controlling corrosion in which the cathode is protected. Cathodic protection is accomplished by suppressing the corrosion current in a corrosion cell and by supplying electrons to the metal to be protected [3]. The principle of cathodic protection can be explained with the help of a typical corrosion reaction of a metal M in an acid medium [2].

Cathodic protection of a structure can be done by following ways:- by an external power supply, i.e. galvanic coupling. Most of the pipelines and marine structures are protected by using this method. Both the anodes and the objects to be protected (cathode) are connected to direct current (dc) supply. Usually, the buried anode materials are inert materials and natural cathodes are steel pipelines or tanks to be protected. However, with the aid of the dc power supplies the natural polarities of the materials are reversed and steel pipelines are cathodically protected. Cathodic coupling by galvanic coupling is realized by using active metal anodes, for example, zinc or magnesium, etc.

Anodic protection is one of the more newly developed electrochemical methods for controlling corrosion. Anodic protection is based on the principles of passivity and it is generally used to protect structures used for the storage of sulphuric acid [2]. The difference between anodic protection and cathodic protection is how the metal to be protected is polarized. The component to be protected is made as anode in anodic protection. Since the anodic protection is based on the phenomenon of passivity, metals and alloy systems, which exhibit active passive behavior when subjected to anodic polarization, can be protected by anodic polarization. Anodic protection is used to make a protective passive film on the metal or alloy surface and thereby controlling the corrosion.

CONCLUSION

Reinforced concrete structures have the potential to be terribly sturdy and capable of withstanding a variety of adverse environmental conditions. However, failures in the structures occur as a result of corrosion in the

reinforcement of the concrete. The ability to continuously monitoring the concrete cover and steel could thus help us to provide information regarding the performance of the structure. Additionally properly observing the structures for corrosion performance and taking appropriate measures at the suitable time might facilitate in a huge amount of money saving. Moreover, the repair operation themselves are quite advanced and need special treatments of the cracked zone and in most instances, the life of the repair is proscribed. Thus, it is helpful for using different monitoring techniques like Open circuit potential (OCP) measurements, Surface potential (SP) measurements, Concrete resistivity measurement, Linear polarization resistance (LPR) measurement, etc. which helps to find the corrosion rate of concrete, reinforcement so that we can apply different suitable preventive methods to protect the reinforcements from its quality degradation and its exposure to the environmental conditions, which will eventually reduce the effects of corrosion, leading to the loss of people, property, structures, economic and financial losses.

REFERENCES

1. "Corrosion of Reinforced Steel in Concrete and Its Control: An overview", by MA Quraishi, DK Nayak, R Kumar and V Kumar; Quraishi et al., J Steel Struct Constr 2017, 3:1
2. "Understanding the Process of Corrosion in Reinforced Concrete", by Ottawa-based company, Giatec Scientific Inc. ; May 30, 2019 <https://www.giatecscientific.com/author/giatec/>
3. " A Review on Corrosion Mechanism of Reinforced Concrete Degradation", by Bruno HUET , Valérie L'HOSTIS , Hassane IDRISSEI , Isabelle TOVENA ; published in Researchgate <https://www.researchgate.net/publication/321128478>
4. Quraishi MA, Kumar V, Abhilash PP, Singh BN (2011) Calcium Stearate: A Green Corrosion Inhibitor for Steel in Concrete Environment. J Mater EnvironSci 2: 365.
5. Mehta PK, Monteiro PJM (2006) Concrete Microstructure, Properties, and Materials. pp: 177-178.
6. Isgor OB, Razaqpur AG (2006) Modelling steel corrosion in concrete structures. Materials and Structures 39: 291-302.
7. Gaidis JM (2004) Chemistry of corrosion Inhibitors. Cement and concrete composite 26: 181-189.
8. Mullick DAK (2004) Corrosion of reinforcement in concrete-an interactive durability problem. The Indian Concrete Journal. 74: 168-175.
9. Ormellese M, Berra M, Bolzoni F, Pastore T (2006) Corrosion inhibitors for chlorides induced corrosion in reinforced concrete structures. Cement and Concrete Research 36: 536-547.
10. Hussain SE, Al-Gahtani AS, Rasheeduzzafar E (1996) Chloride threshold for corrosion of reinforcement in concrete. ACI Materials Journal pp: 534-538.
11. Ahmad S (2003) Reinforcement corrosion in concrete structures, its monitoring and service life prediction- a review. Cement and Concrete Composites 25:459-471.
12. Mohammed TU, Otsuki N, Hamada H (2003) Corrosion of Steel Bars in Cracked Concrete under Marine Environment. ASCE Journal of Material in civil Engineering 15: 460-469.
13. Ramesh MN, Reddy PS (2001) Sacrificial anode for enhancing the durability of concrete repairs. Rehabilitation and repair.
14. IS: 456-2000 Plain and reinforced concrete-code of practice. Bureau of Indian Standard, New Delhi.
15. Neville PA (1983) Corrosion of reinforcement Concrete. pp: 48-50.
16. Chung L, Kim JHJ, Yi ST (2008) "Bond strength prediction for reinforced concrete members with highly corroded reinforcing bars", Cement & Concrete Composites 30: 603-611.
17. Skoglund P, Silfwerbrand J, Holmgren J, Tragardh J (2008) "Chloride redistribution and reinforcement corrosion in the interfacial region between substrate and repair concrete a laboratory study", Rilem Journals, Materials and Structures 41: 1001-1014.
18. "Deterioration of Concrete Due to Reinforcement Steel Corrosion", by J. G. Cabrera CEMU, University of Leeds, Leeds LS2 9JT, UK(Received 16 June 1995; accepted 4 January 1996)Cement & Concrete Composites 18 (1996) 47-59
19. "Residual Strength of Corrosion-Damaged Reinforced Concrete Beams", by Abul K. Azad, Shamsad Ahmad, and Syed A. Azher ; **ACI Materials Journal; Farmington Hills** Vol. 104, Issue. 1, (Jan/Feb 2007): 40-47.
20. "DEVELOPMENT OF AN ALTERNATIVE CRITERION FOR RESIDUAL STRENGTH OF CORROSION DEFECTS IN MODERATE-TO HIGH-TOUGHNESS PIPE", by Denny R. Stephens and Brian N. Leis Battelle Energy Products Division.
21. "Corrosion Monitoring of Reinforced Concrete Structures – A Review" , by Ha-Won Song, Velu Saraswathy ; published in International Journal of Electrochemical Science ;*Int. J. Electrochem. Sci.*, 2 (2007) 1- 28
22. "Repair of concrete structures in marine environment: optimization of concrete removing and cover", by F. Schoefs & E. Bastidas, B. Capra; published in Researchgate

23. "Corrosion assessment of infrastructure assets in coastal seas", by Benjamín Valdez, Jorge Ramirez, Amir Eliezer, Michael Schorr, Rogelio Ramos & Ricardo Salinas ;ISSN: 2046-4177 (Print) 2056-8487 (Online) Journal
24. "Introduction to Corrosion and its Prevention", by Environmental Degradation of Engineering Materials, EDEM 2003, Bordeaux
25. "Materials and Methods for Corrosion Control of Reinforced and Pre stressed Concrete Structures in New Construction", by T. Paul Teng; PUBLICATION NO. 00-081 AUGUST 2000
26. "On-site measurements of corrosion rate of reinforcements", by C. AndradeU, C. Alonso; published in Construction and Building Materials 15_2001. 141-145
27. "Repair and Rehabilitation of Structures", by Mrs. S.SHYAMALA GOWRI, ASSISTANT PROFESSOR, DEPARTMENT OF CIVIL ENGINEERING, SASURIE COLLEGE OF ENGINEERING
28. Rodríguez J, Ortega LM, Casal J, Díez JM. Corrosion of reinforcement an service life of concrete structures. 7th Int. Conference on Durability of Building Materials and Components, Stockholm, June 1996, 1996.
29. Twi-global, Technical knowledge , FQA <https://www.twi-global.com/technical-knowledge/faqs/what-is-corrosion>
30. "The effect of corrosion on the structural reliability of steel offshore structures", by Robert E. Melchers, published in Science Direct
31. ASTM C876-91(1999) Standard test method for half-cell potentials of uncoated reinforcing steel in concrete.
32. H.R.Soleymani and M.E.Ismail, Cem. Concr. Res. 34 (2004) 2037
33. J.P. Broomfield, Techniques to assess the corrosion activity of steel reinforced concrete structures. In: N.S. Berke, E. Escalante, C.K. Nmai and D. Whiting editors, ASTM STP 1276(1996), p. 91-106.
34. K.R. Gowers, S.G. Millard, J.S. Gill and R.P. Gill. Brit Corr J 29 (1994) 25
35. K.R. Gowers, S.G. Millard, J.S.Gill. NACE, Corrosion 92, Paper 205.
36. K.C. Clear. Transport Res Record 1211 (1989) 28