EXPERIMENTAL STUDY TO CONTROL REBAR CORROSION IN A RCC MEMBER THROUGH SACRIFICIAL ANODE CATHODIC PROTECTION METHOD

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THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY
(STRUCTURAL ENGINEERING)

SUBMITTED BY

AMRESH KUMAR
JUNE 2017

DELHI TECHNOLOGICAL UNIVERSITY
NEW DELHI, INDIA

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DELHI TECHNOLOGICAL UNIVERSITY
CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"EXPERIMENTAL STUDY TO CONTROL REBAR CORROSION IN A RCC MEMBER THROUGH SACRIFICIAL ANODE CATHODIC PROTECTION METHOD"** by **"AMRESH KUMAR"** in partial fulfilment of requirement for the award of degree of M.Tech. (Structural Engineering) submitted in the Department of Civil Engineering at **DELHI TECHNOLOGICAL UNIVERSITY, NEW DELHI**

Signature of the Student

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Signature of the Supervisor

The M. Tech Viva- Voce Examination of **AMRESH KUMAR** has been held on ……………… and accepted.

Signature of the Supervisor | Signature of the External Examiner

Signature of H.O.D.

ABSTRACT

Steel reinforcement corrosion in concrete is a complex electrochemical process. Electrochemically active areas namely anode and cathode are created on the steel surface in concrete due to various factors related to steel rebar and the surrounding environment of steel in concrete. The steel rebar undergoes dissolution (corrosion) at anodic area. The presence of cathodic site is essential to support the balancing chemical reaction although no corrosion takes place at cathode.

Cathodic protection is a technique where the steel reinforcement is protected from corrosion by converting it in to a cathode through supply of electrons from an external anode. Two methods i.e. Sacrificial anode cathodic protection (SACP) method and Impressed current cathodic protection (ICCP) method are very useful cathodic protection (CP) method to control/arrest the on-going corrosion of steel in concrete structures.

This report first presents a brief review of steel reinforcement corrosion in which the importance of steel reinforcement corrosion monitoring in concrete are discussed, different techniques for evaluating the state of steel rebar corrosion of RCC structures, especially half-cell potential (HCP) technique are elaborated, and various techniques involved in the repair of corrosion affected concrete structures are presented, and then the results of an experimental based demonstrative study where a corroding steel reinforcement in a concrete beam was repaired through sacrificial cathodic protection technique by attaching zinc plates to the cleaned reinforcement are presented. The progress/regression of corrosion before and after application of the protection method potential was monitored through measurement of corrosion potential. The test result observations show that the corrosion potential, after repair, moved in positive (less corrosion) direction, indicating that the protection method adopted can arrest steel rebar corrosion in RCC structures.

It was concluded that the sacrificial anode based cathodic protection technique can be adopted to protect reinforcement from corrosion in structures where concrete cover is low and cannot be increased due to various reasons, and where impressed current cathodic protection technique is not suitable or uneconomical.

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AMRESH KUMAR

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Chapter 1- INTRODUCTION

1.1 Corrosion of metals and corrosion of steel in concrete

Corrosion is a thermodynamically spontaneous and unavoidable reaction of metals with the surrounding environment. It is essentially a reverse reaction to the metallurgical process of production of metal from raw ores. Under normal condition all metals, except gold and platinum are thermodynamically unstable and therefore undergo corrosion

Steel reinforcement in cement concrete members also undergoes corrosion. Concrete is highly alkaline and acts as a barrier between the aggressive elements present in the environment and the reinforcement of the R.C.C. Therefore steel reinforcement is believed to be protected from corrosion i.e. the rate of corrosion of steel rebar is too slow to be of concern. The thick concrete cover acts as a barrier between aggressive chemicals, such as chlorides from marine environment or soils, or atmospheric carbon dioxide, and the steel reinforcement and, the high alkalinity of concrete protect rebar from corrosion. However, with time, aggressive chemicals penetrate concrete through its porous matrix which ultimately reaches the steel and starts corroding it. The corrosion of rebar cannot be stopped but it can be delayed or slowed down by preventive or protective methods.

The corrosion of concrete rebar is an "electrochemical reaction" in which two active sites i.e. anode and cathode, are formed on surface of steel owing to differences in the concentration of oxygen, moisture, steel composition, and differences in surface characteristics of steel. A schematic of the corrosion process of steel in concrete is shown in Figure 1.

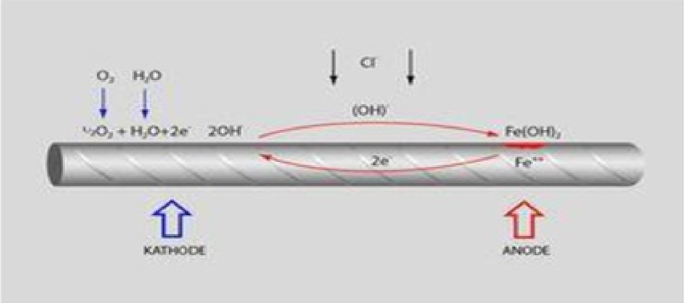


Figure 1: Basic Corrosion Process

The factors affecting the steel corrosion and the detailed mechanism of the same are discussed in Chapter 2.

1.2 Effect of steel rebar corrosion in concrete

Due to corrosion of steel in RC structures initially small cracks are developed which if not controlled than spalling of concrete takes place. The damage process due to corrosion of steel in RCC structure is explained in the form of flow chart in Figure 2.

Ingress
⇩
Corrosion
⇩
Expansion
⇩
Cracks
⇩
Spalling

Figure 2: Flow Chart of Damage Process in RCC Structures

Example of cracks and spalling of concrete due to corrosion of rebar in concrete structures can be seen in Figure 3. Due to corrosion debondment between concrete and steel takes place and as a result spalling occurs.

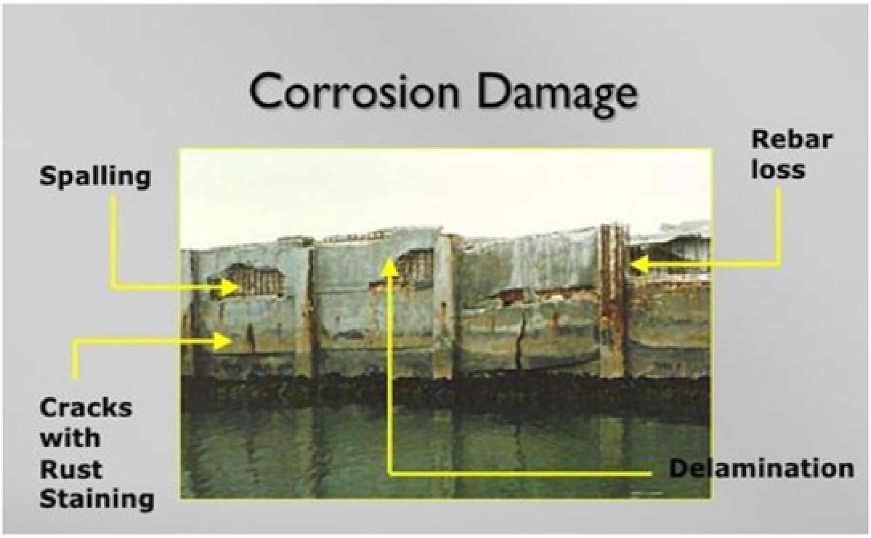


Figure 3: Corrosion Damages of concrete rebar

The effects of steel corrosion in concrete are shown in Figures 4, 5 and 6

Figure 4: Spalling of concrete slab due to corrosion [1]

Figure 5: Cracks formed in RCC Column, Rebar gets exposed [2]

Figure 6: Corrosion of rebar in bridge beam [3]

1.3 Cost of corrosion

In recent years, the attention towards the corrosion of steel in concrete has increased due to its widespread occurrence in certain types of structures therefore cost of repairing such kind of structures are high. In 1960 for the first time an attempt was made by Dr. Rajagopalan (CSIR) to estimate the cost of corrosion in India.

The average cost of corrosion for most of the industrialized nations is 3.5–4.5% of the GNP [4]. In the Arabian Gulf coastal region approx. 95% of concrete damage is caused by reinforcement corrosion and consequent spalling of concrete [4].

The annual cost of corrosion in India during 2011-2012 was nearly US $66 billion or 6% of India's GDP [5]. The per capita cost of corrosion in India is US $55 [5]. The Construction sector followed by the agricultural and manufacturing sector contributes significantly to the cost of corrosion. [5]

Civil structures are designed for different life spans varying from 25-35 years in case of offshore platforms to as long as 100-200 years in case of bridges and dams as given in Table 1.[6] Design service life of different types of structures is given in Table 2.[7]

Table 1: Expected Lifetime of Concrete Structure

Civil Work	Expected Lifetime (years)
Housing	60-100
Dams	100-200
Industrial buildings	30-60
Bridges	100-120
Offshore Platforms	25-35
Nuclear containments	30-50

Table 2: Design Service Life of Different Structures

Service Life (in yr)	Examples
10	Temporary Structures (Structures or parts of structures that can be dismantled with a view to being re-used are not to be considered temporary)
10 – 25	Replaceable structure parts. E.g. Gantry girders, bearings
15 – 30	Agricultural and similar structures
50	Buildings and other common structures
100	Monumental buildings, bridges and other civil engineering structures

Reinforced concrete structures are expected to be maintenance-free during their service lives. However, the modern structures often deteriorate prematurely, resulting in huge loss to the economy. Many of R.C.C structures are exposed to aggressive environment, and significant numbers of bridges in coastal areas are subjected to corrosion attack. The cost of repair constitutes a considerable part of annual budget. In addition to direct economic loss the consequence of corrosion, for example, in the bridges or high rise buildings could be far beyond the economic loss.

With necessary understanding of corrosion of steel rebar in concrete and detection of corrosion on time by proper monitoring the structures, suitable measures can prevent or delay the corrosion of steel rebar in concrete, which can save wastage of manpower and huge amount of money to repair and rehabilitation of damaged structure and potentially serious accidents can be avoided.

Detoriation of RCC structure due to corrosion of the rebar can be treated by conventional repair or by electrochemical repair (cathodic protection) method. Conventional repair involves removal of deteriorated concrete, replacing or cleaning of corroded steel as per the condition of the corroded steel and application of the repair material. On the other hand the electrochemical repair method does not involve removal of concrete and the corrosion can be controlled through the application of an electric current either through sacrificial anodes or inert anodes (impressed current). Cathodic Protection has been recognised as the only means, of controlling the ongoing steel corrosion and extends the life of RCC structures, deteriorating due to steel rebar corrosion in RCC structures.

1.4 Objective and Methodology

The aim of this study is to explore the usefulness of sacrificial anode method to control or minimise the ongoing steel corrosion and investigate the effectiveness of sacrificial anode based method for repair of a corroding RCC beam.

Galvanic anodes were fixed to the corroding steel reinforcement of a RCC beam member to control corrosion. The galvanic anodes function as sacrificial anodes and undergo corrosion in preference to reinforcing steel.

1.5 Scope

The application of the sacrificial anode cathodic protection was carried out on a RCC beam member cast in laboratory using carbon steel and concrete of M 35 grade. Commercially available zinc plate was used as the sacrificial anode.

1.6 Organisation of thesis

The first chapter discusses the basics of steel corrosion on RCC structure. The annual loss of economy due to corrosion in terms of GDP of a nation is discussed in this section as estimated by different scientists from time to time. Affect of steel corrosion its protection methods, its repair technology and the cathodic protection as viable repair technique for RCC structures is also discussed.

The second chapter consists of literature survey where factors related to durability and deterioration of concrete, exposure condition, types of steel corrosion and factors affecting steel corrosion of RC structure are explained. Further methods of monitoring steel corrosion and method of preventing steel corrosion are discussed. In the end, different suitable methods of protecting structural steel corrosion are discussed and an appropriate method is selected for the repair of corroded beam element. Monitoring the corrosion of steel in concrete is discussed using half-cell potential technique. Detailed procedure for repair of corroded structure using sacrificial anode method is discussed.

The details of the experimental study are discussed in Chapter Three, which include RCC beam dimensions, monitoring of corrosion, repair of corroding steel, etc.

Results of the experimental setup are discussed in Chapter Four. In this chapter grid diagrams showing the points at which readings were taken using half-cell potential instrument. With the help of these readings a comparative table and graphical representation is shown in this chapter which helps to interpret the results properly.

In Chapter Five conclusion of the experiment is discussed and the summary of the report is presented.

This chapter consists of process and mechanism of corrosion in RCC structures. Further it discusses the factors affecting the process of corrosion, types of corrosion, affect of corrosion on RCC structure. At the end of the chapter the repair method for the corroded structure is discussed.

2.1 Steel reinforcement corrosion in concrete

The steel reinforcement corrosion in concrete is an electrochemical reaction in nature and required basic elements for corrosion are:-

1. Anode: - at anode corrosion occurs and current flows from
2. Cathode: - at cathode no corrosion occurs and current flows to
3. Electrolyte: - it is a medium of ionic current flow like soil, water or concrete
4. Metallic Path: - connecting link between anode and cathode for current return and ensure the completion of circuit.

In the process of corrosion of rebar in concrete two electrochemically active sites (i.e. anodes and cathodes) with different electrochemical potential develop. The difference in potential arises due to the differences in environment of the concrete around steel. The anodic and cathodic regions are formed due to different concentration of salt in the pore solution as access to oxygen is non-uniform. Generally only one metal is present in RCC structures, due to the reasons mentioned above anodic and cathodic sites are created at many places on the steel of concrete structure. At the anode and cathode sites, chemical changes take place. An electrochemical cell is formed between anodic and cathodic region connected by pore solution (electrolyte), which is generally very alkaline i.e. pH range of the concrete is 12 to 14.

A corroding (oxidation reaction) takes place at the anode in which the positive ferrous Fe^{++} ions present at anode move through solution and negative free electron e^- move via steel to cathode region at which e^- gets consumed in a cathodic reaction to form hydroxyl ion (OH^-). Hydroxyl ions combine with Fe^{++} ions to form Ferric hydroxide which with further oxidation converts to rust. Figure 1 shows the process and involved reactions are (13):-

Reaction at Anode:-

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

$$Fe^{++} + 2(OH)^- = \underset{\text{(Ferrous hydroxide)}}{Fe(OH)_2} \quad (2)$$

$$4Fe(OH)_2 + 2H_2O + O_2 = \underset{\text{(Ferric hydroxide)}}{4Fe(OH)_3} \quad (3)$$

$$H_2O + O_2 + 2Fe(OH)_3 = \underset{\text{Hydrated Ferric Oxide (Rust)}}{Fe_2O_3H_2O + 2H_2O} \quad (4)$$

Reaction at Cathode:-

$$4e^- + O_2 + 2H_2O = 4(OH)^- \qquad (5)$$

For corrosion process to continue O_2 and H_2O is needed therefore no corrosion takes place in dry structure or fully submersed structures. The transformation of structural steel to rust is extended to increase in volume of rust which depends upon state of oxidation. The increase in volume of rust can be upto 600% of original volume of steel, due to which concrete expends and cracking takes place, which further accelerates the corrosion process of steel reinforcement in concrete.

2.2 Causes of Steel reinforcement corrosion in concrete

The inward movement of chlorides and carbon dioxide in aquous form into the concrete are responsible for start of steel reinforcement corrosion in concrete.

2.2.1 Chloride

The steel reinforcement in concrete is protected from external environment due to high alkalinity of concrete and the cover concrete. This passive layer is destroyed by chlorides in marine environment (often called chloride attack) and this will lead into pitting or localized corrosion. The presence of chloride in concrete is one of the main cause of steel reinforcement corrosion in concrete. Generally, chloride induced corrosion is common in RCC structures.

Chloride induced corrosion are as follows:-

1) Localised and very high rate of corrosion takes place due to separate region of anode and cathode.

2) After the initiation of corrosion it is very difficult to remedy.

Different ways in which chloride can be cast in concrete are:-

1) Contaminated aggregates
2) Chloride used as accelerator
3) Water contaminated with chloride

Ingress of chloride in concrete:-
1) Direct wetting with sea water and spray of sea salt
2) Melting of icing salts in Himalayan region
3) Using chloride contained chemicals

The chloride entering into concrete manifests itself in two different forms in the concrete:-
1) Chloride dissolved in pore solution (Free chloride)
2) Cement gel adsorbed chloride (Bound chloride)

Initially free chloride is responsible for the initiation of corrosion of steel reinforcement in concrete. The bound chloride first gets dissolved in the solution to become free chloride then it reacts with the steel in embedded in concrete. The type of binder, amount of pore solution, rate of hydration and other ion in pore solution defines the relation between free chloride and bound chloride. Higher concentration of tricalcium aluminate adsorbs more chloride therefore content of chloride ion in pore solution is low. Binding capability is defined by alumina and iron oxide present in cement. Fly ash cement has great chemical binding capacity as it constitutes higher amount of alumina and iron oxide. Slag cement has high physical binding capacity as it forms finer hydrated products.

If concentration of hydroxide is high then concentration of chloride will be less in pore solution. The chloride binding capacity varies with variation in temperature. With the increase in temperature the quantity of bound chloride decreases. Alkalinity, curing time and temperature of curing are some other factors which influence the chloride binding capacity of concrete.

Passive covering of steel is not disrupted if concentration of chloride ion in pore solution is low. In pore solution if chloride concentration or ratio of chloride to hydroxide crosses “chloride threshold” than the steel reinforcement corrosion in concrete is sever.

Corrosion of steel reinforcement in concrete is greatly influenced by the chloride ion concentration. Therefore determination of chloride level in concrete is important to evaluate the extent of corrosion of steel reinforcement in concrete. Generally chloride measuring methods are destructive where sample of concrete powder is dissolved in acid. The measured result is termed as the acid-soluble or total chloride in concrete.

To measure the chloride content of concrete following methods are used:-

(i) Quantab chloride titrator strips
(ii) Argentometric digital titration
(iii) Specific ion probe and Potentiometric titration.

Potentiometric titration has been considered as standard method to measure chloride content of concrete. It is a laboratory method and is time consuming and expensive. Quantab chloride titrator strips and specific ion probe methods are field methods of which Specific ion probe technique high accuracy and is convenient to measure chloride in field.

2.2.2 Carbon dioxide

The passive layer of the cover concrete is destroyed by carbon dioxide present in the atmosphere (causing carbonation of concrete). Carbonation usually induces a generalized corrosion. Carbon dioxide present in concrete (carbonation) is another main cause of corrosion of rebar in concrete. Carbonation occurs when carbon dioxide in atmosphere reacts with hydroxide present in concrete. The process of carbonation is described below in equation 6 and 7:-

$$CO_2 + H_2O = H_2CO_3 \qquad (6)$$

$$H_2CO_3 + Ca(OH)_2 = CaCO_3 + H_2O \qquad (7)$$

Due to carbonation the pH value of pore solution decreases, therefore when pH of pore solution is less than 9 the corrosion reaction in steel reinforcement of concrete is initiated. Carbonation can change the pore structure of concrete so its effect can also be seen on diffusion of chloride in concrete. Due to carbonation chloride binding capacity of concrete decreases as cement gel gets converted to crystalline products and pH of the pore solution is decreased. Total porosity decreases, redistribution of pore sizes occur and the proportion of large pores increases. It is more significant for blended cements than OPC.

A destructive method is used to measure the carbonation in concrete. In this method a freshly cut core of concrete is used over which phenolphthalein indicator solution is sprayed. Solution made for best result consists of phenolphthalein one gram in a solution (of 100ml) containing alcohol and water in the ratio of 1:1. This method is commonly used as it is practical, reliable and accurate.

2.3 Factors affecting steel reinforcement corrosion in concrete

The behavior of corrosion in steel reinforcement of concrete depends upon the chemical properties of steel, concrete and there interfacial zone. Steel reinforcement corrosion in concrete is not governed by single factor, so steel corrosion in concrete is a complicated process. The interaction among these factors is important for corrosion to take place on steel reinforcement in concrete.

Liu and Weyers[14] stated that "the dynamic corrosion process of steel in concrete is a function of the chloride content, temperature, resistivity of the concrete and active corrosion time". However in general the following factors influence the extent/ rate of steel reinforcement corrosion in concrete:-

2.3.1 Design of the structure

As per IS:456-2000 and IRC 112-2011 keeping in view the requirements of the performance and durability.

2.3.1.1 Thickness and homogeneity of cover to steel in RC structures

Time for corrosive chemicals to reach the steel in concrete is determined by thickness of the cover concrete. Sometimes, by increasing the thickness of the cover concrete the service life of RCC structure can be increased. Nominal cover to be provided to the steel reinforcement in concrete depends upon the exposure condition. The minimum nominal cover provided to RCC structures are mentioned in clause 26.4.2 of IS: 456-2000 which is shown in Table 3.

Table 3: Recommended Nominal Cover for Durability Requirements

S.No.	Exposure Condition	Minimum Cover (mm)
1	Mild	20
2	Moderate	30
3	Severe	45
4	Very severe	50
5	Extreme	75

2.3.2Constituents of the reinforced concrete structure

Concrete is a composit material which is formed by mixing cement, aggregate, admixture and water. Therefore quality of concrete depends upon quality and type of constituents used for making concrete. The main constituents used in reinforced cement concrete structures are cement, aggregate, admixture, water and steel.

2.3.2.1 Cement

The cement used should be appropriate for the intended use. Blended cement has received considerable attention due to their improved durability performance in severe condition. Appropriate quantity of cementitious material is a critical factor for ensuring the durability of the structures in the given exposure conditions. Blended cements have received considerable attention due to their improved durability in aggressive exposure conditions. Blended cements contain fly ash, silica fume and GGBFS. The service life of plain Portland cement concrete is several times shorter than the blended cement concrete. Addition of silica fume in concrete reduces water absorption and permeability. Therefore penetration of water, chloride and carbon dioxide becomes difficult which benefits in resisting corrosion of steel reinforcement in concrete. The recommended minimum quantities of cement for different exposure conditions in the concrete according to clause 26.4.2 of IS: 456-2000 is shown in Table 4.

Table 4: Minimum Cement content for Different Exposure Condition

S.No.	Exposure Condition	Minimum cement content (kg/m^3)
1	mild	300
2	moderate	300
3	severe	320
4	very severe	340
5	extreme	360

2.3.2.2 Aggregate

Aggregate used should comply with the IS: 383. An aggregate free from harmful chemicals and suitable in parameters like durability and strength of concrete is used for concreting purpose. The aggregates selected should not have water absorbing capacity more than 10% and should not contain sulphate as SO, more than 0.5% of its mass.

2.3.2.3 Admixture

Admixture used should conform to Indian standards IS: 9103. They should ensure uniform blending with cement. Admixture should not affect the durability of concrete and it should not combine with the constituent of concrete to form harmful compounds and should not increase the risk of corrosion of steel in concrete.

2.3.2.4 Water

Water which is used for mixing of concrete constituents and for curing purpose should be clean and free from salts, oil, alkalis, acids, organic materials, sugar or other substances which can detoriate steel or concrete. Mixing of concrete with sea water is strictly prohibited as it contains harmful salts.

The w/c ratio greatly influences the porosity of concrete. Concrete with high w/c ratio produces concrete with high porosity through which harmful chemicals can easily penetrate. Steel reinforcement in concrete with high porosity is more susceptible to corrosion than steel in less porous concrete. The recommended water-cement ratio for different exposure condition according to 8.2.4.1 IS: 456-2000 are shown in Table 5

Table 5: Water-Cement Ratio for Different Exposure Conditions

S.No.	Exposure Condition	Maximum water-cement ratio
1	Mild	0.55
2	Moderate	0.50
3	Severe	0.45
4	Very Severe	0.45
5	Extreme	0.40

2.3.2.5 Steel

Steels are differentiated on the basis of their microstructure and composition and as different steel has different composition so there corrosion behavior in concrete is also different. In Europe stainless steel and stainless steel clad has been used for many years as corrosion resistant steel reinforcement in concrete instead of carbon steel bars. Laboratory examinations and field tests carried out in the world showed that stainless steel are more resistant against corrosion than carbon steel. The rate of corrosion of stainless steel is lower than that of carbon steel as chloride tolerance of stainless steel is many times higher than that of black steel. Austenitic steel shows no corrosion even in high chloride environment, therefore its performance is better than stainless steel and carbon steel. Stainless steel bars are capable of resisting corrosion in severe chloride environment, but it is costlier than carbon steel. In most concrete structures, deformed carbon steel lasts long enough to satisfy the designed service life of the structure, so it is not worth using the expensive stainless steel. Only in some very important reinforced elements, for which no corrosion is permitted, would stainless steel be considered. In this case, the increase of the overall cost is not too high considering fewer repairs and less maintenance costs.

Steel surface has direct effect on the bond between reinforcement and concrete, therefore influences the failure of structure. It was found that the rust which was well adhered to the underlying steel helped the bond between steel and concrete. The surface of steel treated with water to form a coating before incorporating of steel in concrete could increase the bond strength. Slight corrosion could increase the bond strength, whereas severe corrosion decreases it.

According to IS 456-2000 reinforcement used should be of following types:-

1. Medium tensile steel and mild steel bars conforming to IS 432 (part 1)
2. Deformed high strength steel bars conforming to IS 1786
3. Hard Drawn steel wire fabric conforming to IS 1566

2.3.3 Concrete

The quantity and type of aggregate, cement, admixture and w/c ratio govern the performance of concrete. Chemical additives, containing chlorides are capable of accelerating the steel reinforcement corrosion in concrete.

Different grade of concrete for different exposure conditions recommended by IS: 456-2000 is shown in Table 6.

Table 6: Minimum grade of concrete for different exposure conditions

S.No.	Exposure Condition	Minimum grade of concrete
1	mild	M20
2	moderate	M25
3	severe	M30
4	very severe	M35
5	extreme	M40

2.3.4 Construction

2.3.4.1 Compaction

Concrete should be adequately compacted without segregation by maintaining proper workability and employing appropriate placing and compacting equipments. Proper compaction is very important at movement joints and embedded bars. If concrete is defect free and properly compacted than it acts as resistant towards corrosion of steel reinforcement in concret.

2.3.4.2 Curing

The process of preventing loss of moisture from the concrete while maintaining a satisfactory temperature is called curing. Curing in early stage of structure after casting of concrete is very important to compensate the heat of hydration generated during the process of setting of concrete. If curing is not done cracks may develop on the surface of structure. Different types of curing such as moist curing, membrane curing etc. are often adopted in concrete construction.

2.3.4.3 Permeability of Concrete

Higher porosity and large pore sizes helps in penetration of oxygen, chloride, carbon dioxide, moisture and other harmful chemicals from the environment into concrete. Therefore, the permeability directly affects the corrosion processes. Permeability has influence on ion flow in concrete; therefore it also influences the rate of corrosion of steel reinforcement in concrete.

Concrete with low permeability resist the penetration of harmful chemicals from environment into concrete and the possibility of steel reinforcement corrosion in concrete will be low. Permeability of cover concrete can be reduced by better w/c ratio, proper compaction and use of admixture etc.

2.3.4.4 Pore solution of concrete

In the pore of the concrete pore solution exists which acts as an electrolyte. Reaction of pore solution with the reinforcement of the concrete leads to corrosion of steel surface in concrete.

The pore solution contains various ions, such as sodium, potassium, calcium, hydroxyl, sulphate and sulphite etc. The composition of the pore solution varies with the cement used and the age of concrete. The pore solution of mortar made of standard Portland cement without admixture has pH of approx. 13.5 with K^+, Na^+ and Ca^{2+} as the main cations. Besides the main components, other species can be introduced by supplementary cementitious additives, aggregates, chemical additives and outside environment.

The high pH will facilitate the formation of passive layer or protective layer on steel surface and protects it from corrosion, however when chloride ion penetrate into concrete than passive layer is destroyed and corrosion of steel is initiated. Similarly, when carbon dioxide in aqueous form enters into concrete it will reduce the pH of pore solution due to which leads to breakage of passive layer leading to breakdown of the passive layer resulting in corrosion of steel reinforcement in concrete.

2.3.5 Exposure conditions

Classification of environment or exposure conditions to which structures are subjected to during the service life of the structure is classified into five categories according to clause 8.2.2.1 of IS: 456-2000 which is mentioned in Table 7.

Table 7: Environmental exposure condition

S.No.	Environment	Exposure Condition
1	mild	Concrete surfaces protected against weather or aggressive conditions, except those situated in coastal area.
2	moderate	Concrete surfaces sheltered from severe rain or freezing whilst wet. Concrete exposed to condensation and rain. Concrete continuously under water. Concrete in contact or buried under non-aggressive soil or ground water. Concrete surfaces sheltered from saturated salt air in coastal area.
3	severe	Concrete surface exposed to severe rain, alternate wetting and drying or occasional freezing whilst wet or severe condensation. Concrete completely immersed in sea water. Concrete exposed to coastal environment.
4	very severe	Concrete surfaces exposed to sea water spray, corrosive fumes or severe freezing condition whilst wet.
5	extreme	Concrete in contact with or buried under aggressive subsoil or ground water surface of members in tidal zone members in direct contact with liquid or solid aggressive chemicals.

2.3.5.1 Moisture

The moisture content has significant influence 77 the corrosion rate of steel reinforcement in concrete. Dry concretes do not undergo reinforcement corrosion and also rate of corrosion is significantly reduced in a concrete fully submerged in water. Ho13ver, for structures which undergo alternate wetting and drying condition the observed rate of corrosion of steel reinforcement in concrete is very severe.

2.3.5.2 Temperature

The rates of all the chemical reactions accelerate with increase in temperature so is the corrosion process of steel in concrete. Increase in temperature will lead to increased movement of the ionic species rates and hence wi76crease the rate of corrosion. It has been reported that a rise in temperature by 10 ° doubles the rate of corrosion.

2.4 Types of steel corrosion in concrete structures

RCC structures are not always subjected to same environment and the constituents of the structure also vary from structure to structure. Different structures are subjected to different environmental conditions and different constituents therefore nature of corrosion or process of corrosion varies from structure to structure. Due to this different forms of steel corrosion are observed in structures.

The classification of types of corrosion is not absolute as definition of each type of corrosion is applicable for certain condition. For example, corrosion cannot be absolutely uniform. On a steel surface it might look like uniform corrosion but may have localised corrosion on small scale. Pitting can be classified as localised corrosion if pitting site is carefully analysed but it is termed as galvanic corrosion.

Different types of steel corrosion are classified below:-

2.4.1 Uniform Corrosion

In case of fully compacted concrete it is hard to differentiate between the anodic and cathodic area i.e. the anodic and cathodic area are nearly 48rged together along the steel reinforcement in concrete. So anodic and cathodic reactions occur along the steel surface and the uniform dissolution of steel occurs in the steel bar. This is uniform corrosion. The anodic and cathodic sites (A & C) are sometimes at some small distance and randomly distributed and can change from time to time along the steel bar. Therefore, uniform corrosion can also be regarded as the damage caused by many random galvanic cells whose sizes are very small. In carbonated concrete structures generally uniform corrosion is observed.

There is no absolute uniform corrosion in concrete structures. Uniform corrosion is only a relative concept as mentioned above. In most published documents on corrosion of reinforced concrete, the uniform corrosion has not been specifically mentioned. However, most of the fundamental research studies work carried out in laboratory assuming that the studied specimen was uniformly corroded. Also the famous guard ring developed for the field survey of structures was originally designed assuming uniform corrosion under the sensor, even though now it is used to detect the non-uniform distribution of corrosion.

2.4.2 Galvanic Corrosion

Due to the hydrogenity of concrete structures and their micro-environment it is relatively rare for the anodic and cathodic processes to be uniformly distributed along the steel surface. More commonly, at some sites a cathodic process is strong than the anodic process while at other place the anodic reaction is much faster than cathodic reaction.

The rate of galvanic corrosion or galvanic current density (I_g) is determined according to reactions given below:

$$I_g = (Ec_{corr} - Ea_{corr}) / (P_a + P_c + R_c) \qquad (8)$$

Where,
Ec_{corr} = Corrosion potential at cathodic area
Ea_{corr} = Corrosion potential at anodic area

When, $I_g = 0$

P_a = Anodic polarities
P_c = Cathodic polarities
R_c = Concrete resistance between anodic and cathodic areas.

In galvanic corrosion resistivity of concrete is high and anodic and cathodic area can be clearly differentiated so concrete resistance between anodic and cathodic area in galvanic corrosion has very significant role to play in equation (8). From this it can be observed that galvanic corrosion is mainly governed by the resistivity of concrete. As the concrete resistivity increases, rate of galvanic corrosion decreases.

According to equation (8) ratio of cathodic to anodic area is also important to the galvanic corrosion process. Higher ratios will produce faster and more concentrated corrosion damage to reinforcement.

2.4.3 Localized Corrosion

Localized corrosion is the most common form of corrosion observed in field and it is the most dangerous attack on steel. There exists various form of localized corrosion of which pitting and crevice corrosion is common.

In localized corrosion cathodic area is much higher than the anodic area, but rate of corrosion penetration is higher in anodic area. Therefore localized corrosion is an important form of corrosion, because the corrosion cell consists of a small rapidly corroding anodic area and a large cathodic area surrounding the anodic area. The feature of extremely high ratio of cathodic to anodic area makes localized corrosion very dangerous to steel in concrete.

The second feature of localized corrosion (i.e. pitting and crevice corrosion) is its self-catalysis. That is, the anodic dissolution process of steel could generate a more aggressive environment (lower pH value of solution and higher content of chloride ions) in the pit or crevice which in turn facilitates the corrosion dissolution in the pit or crevice. This feature actually distinguishes the localized corrosion from galvanic corrosion. The corrosion would be automatically accelerated in the pit or crevice after it is triggered. For example, the uniform corrosion might slow down as time passes due to barrier effect created by the product of corrosion on steel surface. However, the corrosion situation might be further worsened if the barrier effect occurs in the case of pitting corrosion or crevice corrosion. The barrier effect increases the occlusion degree of the pitting or crevice cells which tend to keep the inner aggressive environment in the pit or crevice from being neutralized by the pore solution outside the pit or crevice. This further promotes the self-catalytic effect; hence corrosion rate might be greatly increased with time in this case. The self-catalytic feature not only makes localized corrosion very dangerous to steel in concrete, but it also makes the corrosion process very complicated and unpredictable.

Pitting corrosion occurs when chloride attacks on some particular site of passive film on steel reinforcement of concrete due to which anodic dissolution of steel reinforcement occurs at those sites. Therefore localized corrosion of steel bar in concrete is closely associated with ingress of chloride. Actually most chloride induced corrosion tends to be localized. During the pitting corrosion, the chloride ions tends to be accumulated in the pits and the pH of the solution in the pits decreases, so the environment inside the pit is getting aggressive; this in turn further accelerates the anodic dissolution of steel in the pits. For pitting corrosion, loss of cross-sectional area takes place due to which strength of steel reinforcement reduces at corrosion sites which is of great concern. A small amount of corrosion products might mean a significant damage to the reinforcement.

When chloride level is not high then the pitting corrosion doesn't occur but crevice corrosion might occur. The mechanism for the crevice corrosion might be still due to the dissolution, the local acidification by ferrous ion hydrolysis and the chloride accumulation processes.

2.4.4 External Current induced corrosion

If steel reinforcement in concrete is subjected to external current source than extra loss of steel reinforcement takes place. As the conductivity of steel is much higher than that of concrete, almost all the induced current will be conducted by the reinforcement in concrete. The site from where external current flow into the steel reinforcement through surrounding concrete only cathodic reaction takes place so severe corrosion might not occur. However, the steel is forced to act as anode at the sites where the induced current comes out of the reinforcement and goes back to the external environment through the concrete. Consequently, iron dissolution takes place in such location, reducing the cross-sectional area of the steel.

The most typical external current induced corrosion is the stray current corrosion, which was once blamed for all the steel reinforcement corrosion in concrete in the 1950s. Most cases stray current corrosion in concrete structures occur where electric trams, trains or buses run through the structure, or where cathodic protection is applied. Screening of the sources of stray current might be the most effective measure to prevent this kind of corrosion damage. The monitoring of stray current corrosion is important.

2.4.5 Cracking due to stress corrosion and hydrogen induced embrittlement

When corrosion medium and steel stresses combine together than cracking due to stress corrosion and embrittlement due to induction of hydrogen takes place. The detection of stress corrosion cracking (SCC) and hydrogen induced embrittlement (HIE) in initial stage is difficult but failure caused due to SCC and HIE are sudden due to breakdown of steel reinforcement which ends into structure failure. Although SCC and HIE do not occur commonly as compared to other forms of corrosion but their occurrence cannot be neglected.

SCC and HIE corrosion depends upon Quality of steel. For example high strength steel is more sensitive to SCC and HIE. As pre-stressed concrete use high strength steel so they are more susceptible to SCC and HIE and this factor should always be considered in pre-stressed concrete structures.

The greatest concern about HIE of reinforced concrete structure is the susceptibility of prestressed tendon especially when cathodically over protected. Theoretically, this is the most dangerous case, even though the applied cathodic protection (CP) current density is not overall high enough to induce HIE, some regions may still be over protected and there exists the HIE risk because the distribution of cathodic protection current density of concrete is not distributed uniformly. According to review, consequences of pre-stressed steel corrosion in concrete were much more critical than that of ordinary steel used in plain reinforced concrete ; cold drawn and stress relieved was less susceptible to hydrogen embrittlement than quenched and tampered steel. Good quality concrete and sufficient cover concrete would provide corrosion protection to the embedded prestressing steel. The main environmental condition that can lead to corrosion of prestressed steel is the presence of chloride. However, it was also found that chloride had no direct effect on the hydrogen absorption rate, but other factors had more influence on HIE.

2.5 Techniques to monitor steel reinforcement corrosion in concrete

Many techniques have been developed to monitor steel reinforcement corrosion in concrete. Generally these techniques are divided into two groups:-

1) Electro chemical and
2) Non-electrochemical

Some of these techniques are discussed below:-

2.5.1 Non-electrocemical Techniques

2.5.1.1 Physical Techniques

Physical technique has been widely used for determination of defects in reinforced concrete structure. Visual inspection, magnetic method, thermography, stress wave technique, radar, radiography etc. are some example of physical technique to monitor corrosion of steel reinforcement in concrete.

The sign of corrosion which can be detected through human eye with the help of camera is called visual inspection method to detect corrosion. Exact extent of corrosion damage cannot be determined by this method. Steel reinforcement corrosion in concrete can be detected by appearance of cracks aligned along the reinforcement and rust staining. After visual inspection some other tests like stress wave technique etc. are carried out to conform the cause and source of deterioration. Delamination by sounding is a standard industrial method provided by ASTM D4580.

Gamma ray and x-ray radiation are used in Radiographic method. For detection of in situ steel corrosion in concrete by this method portable gamma ray is used. This method can detect corrosion state of steel reinforcement in concrete has not been established, but it is reliable method to detect concrete defects. With the help of infrared thermography (IRT) method location and size of delamination can be measured on the surface of concrete. This method cannot provide direct information on steel corrosion but it is fast and reliable method. The reliability of radar method to detect steel corrosion is also doubtful

2.5.2 Non-destructive testing (NDT) Methods

Non destructive testing (NDT) are very useful in situ methods for the evaluation of corrosion of steel reinforcement in RCC structures. These methods are effective in detecting the Effect of steel reinforcement corrosion and homogeneity of RCC structure

2.5.2.1 Electrochemical Method

Electro chemical method is one of the effective NDT methods. As steel reinforcement corrosion in concrete is an electro-chemical process, so electro-chemical methods are developed to detect the corrosion of steel reionforcement in concrete. This is regarded as the most powerful and reliable non-destructive techniques in laboratory and field measurements.

2.5.2.1.1 Open Circuit Potential (OCP) Method

Open circuit potential (OCP) method one of the many electrochemical method present to detect the steel reinforcement corrosion in concrete. In this method the value of electrical potential between steel of RCC structure and reference electrode is measured in terms of mV or V. This gives the value of corrosion potential of steel reinforcement in concrete. The results observed can be used to develop equipotential contours, from which the condition of steel with respect to corrosion gives an indication of the steel condition. This method is time consuming and the closure of facility during the test hour is required because in this method the structure need to be prepared for inspection and testing. Equipment used in this method are Potential electrode, Voltmeter, and connecting wire.

2.5.2.1.2 Resistivity method

Resistance to current flow in ionic path of concrete is called resistivity of concrete and hence is an indicator of the corrosivity of steel reinforcement in RCC Structures.

There are two types of method to measure the resistivity of concrete one is Four probe method based on Wenner principle and other is two probe method. Four-probe method is the commonly used method and two-probe method is rarely used. The four-probe or point technique ensures quick, accurate on field measurement of concrete resistivity. In this method the distance between probe is larger than the maximum size of the aggregate to reduce the effect of aggregate on resistivity readings. Error in readings can also be observed due to the short circuit effect of steel reinforcement in concrete. Structure geometry doesn't influence the resistivity results if the spacing and location of electrode is properly selected. [15]

Risk of corrosion of steel is determined in terms of concrete Resistivity (Ω·cm). Commercial equipment are used which contain voltmeter/resistivity unit, potential electrodes, current electrodes and insulated wires. Relation between corrosion risk and resistivity is shown in Table no.6. [9]

Table 8: Resistivity value for corrosion risk

Resistivity in Ohm.cm	Corrosion risk
>20,000	Negligible
10,000 to 20,000	Low
5,000 to 10,000	High
< 5,000	Very High

2.5.2.1.3 Polarisation resistance

In polarisation resistance method potential is measured by placing an electrode plate on the surface of concrete. Advantages of this method are that it doesn't get effected by the small disturbances and time duration to take readings is very short. Disadvantage of this method is that to receive full response it takes time because electrical capacitance exists between steel reinforcement and concrete. Due to high concrete resistance voltage drop between steel reinforcement and reference electrode is observed. Unit of measurement is

A/cm^2. Equipments used are voltmeter, counter and reference electrode, ammeter and connecting wires.

2.5.2.1.4 Galvanostatic pulse method (GPM)

In this method a current pulse is applied at anode area galvanistatically on the steel rebar with the help of counter electrode which is placed on the surface of concrete. Advantage of this method is that steel corrosion rate in concrete can be measured rapidly. Disadvantage of this method is that due to parallel or crossing steel rebar or cracks and delamination leads to misleading results. Measurement is taken in the form of potential resistance (Rct (kΩ·cm^2)). Equipment used in this method are guard ring, connecting wires, counter and reference electrodes.

2.5.2.1.5 Electrochemical noise (EN)

Electrochemical noise (EN) method describes the fluctuation of potential and current which are generated by the corrosion reaction. Advantage of this method is that measured signals can be analysed mathematically, causes no disturbance to the system and this method is easy to use. Disadvantage of this method is the complicated mixture of different sources of noise due to concrete cracking and corrosion of steel rebar make mathematical analysis difficult. Measurement is taken in the form of Noise resistance (Rn (kΩ·cm2)). Equipment used in this method is working, reference and counter electrodes, data acquisition board, amplifier, ammeter and voltmeter.

2.6 Methods of Preventing Corrosion

There are many techniques which can be used to prevent RCC structure from corrosion but the choice of options left for old structures are very limited. Different techniques used to prevent steel from corroding are:-

2.6.1 Reinforcement Steel Selection

Steel used for RCC purpose cannot be immune to corrosion but by selecting a proper steel bar i.e. stainless steel or plain steel or carbon steel, the rate of corrosion can be reduced. This process of steel prevention can be applied only before the casting of concrete and cannot be used for old structures.

2.6.2 Coatings & Surface Treatments

Coatings for concrete should have property to bridge moving crack while maintaining the integrity of film. To protect the concrete surface three types of surface treatment are available, which can also control ingress of water and chemical.

Three types of surface treatment are described below:-

1) Film formers: - A protective film is formed on the concrete surface which is based on coating system like organic resin (styrene butadiene and acrylic copolymer) or inorganic resin (potassium silicate).

2) Pore blockers: - Materials which partially or completely block the pores in the concrete are called pore blockers. The pores can be physically blocked or can be blocked by using such a material which reacts with concrete to produce products which can block the pores of concrete.

3) Pore liners: - In this method material which line the concrete pore are used. This is called hydrophobic impregnation treatments. One example of such material is silicon impregnate. Their main function is to repel water from concrete surface but at the same time allow water vapour to escape out of concrete.

Different types of coating available on the basis of polymer used are as follows:-
1) Urethane coating
2) Epoxy ester coating
3) Epoxy and acrylic polymer coating
4) Vinyl, acrylic/styrene polymer combined latex coating
5) High solid coating
6) Water soluble coating

Paints or other organic coating is used on steel reinforcement to prevent it from degrading effect of harmful species. This method can be used only in new structures and that too before the casting of concrete. Common coatings on steel reinforcement are:-

- Epoxy Powder coatings
- Inhibited cement slurry coating
- Cement polymer network coating

2.6.3 Corrosion Inhibitors

Those chemicals which react with the surface of metal or the harmful species causing corrosion to stop the corrosion causing reaction are called corrosion inhibitors. Inhibitors gets adsorbed on the surface of metal thereby forms a protective layer on the surface of metal. Dispersion technique is used to apply these chemical on metal surface. Disruption of process of corrosion by inhibitors depends upon:-

1) By changing the polarization behaviour of anode/cathode.
2) By reducing the diffusion of ions to the steel surface.
3) By increasing the electrical resistance of steel surface.

Inhibitors are mainly divided into two categories i.e. cathodic inhibitor and anodic inhibitor.

1) **Cathodic inhibitor:** - These inhibitors reduce the rate of corrosion by retarding the reaction at cathode. At cathodic site a barrier layer of insoluble compound is formed which reduces the active cathode area due to which corrosion rate also decreases. Some commonly used cathodic inhibitors are:-
    1) Magnesium salts
    2) Zinc salts, example: zinc phosphate and zinc hydroxide
    3) Calcium salts, example: calcium phosphate and calcium carbonate
    4) Polyphosphates

2) **Anodic inhibitor:** - These inhibitors reduce the rate of corrosion by retarding the reaction at anode. At anodic site an invisible oxide layer is formed due to which anode potential is increased and oxidation process is decreased. As anodic area gets reduced

so rate of corrosion also decreases. Disadvantage of this method is that at low concentrations it causes increase of corrosion rate, so in this method optimum level of inhibitor content should always be maintained.

Commonly used anodic inhibitors are mentioned below:-

1) Nitrite
2) Orthophosphate
3) Chromate
4) Molybdate

Chemical production, petroleum refining, water treatment facilities and oil and gas exploration are some of the major industries which use corrosion inhibitors. In-situ application of corrosion inhibitor to counter corrosion of metal is the main advantage of this technique.

2.7 Repair techniques for corroding reinforced concrete structures

2.7.1 Conventional methods of repair

In conventional method of repairing the corroded area of concrete, the damaged concrete area is removed, weakened steel due to section loss is replaced and good quality concrete is placed. The disadvantage of this technique is that, as corrosion process is electrochemical in nature, repair process can lead to an acceleration of corrosion in adjacent areas (incipient anode effect).

2.7.2 Electrochemical Process

Conventional patch repairing method is the primary method to repair RCC structures suffering from steel reinforcement corrosion. Apart from conventional method repairing RCC structures electrochemical techniques like cathodic protection, electrochemical chloride extraction and electrochemical re-alkalisation are useful techniques to control or prevent the steel reinforcement corrosion in concrete. Different types of electrochemical techniques are discussed below.

2.7.2.1 Cathodic protection (CP)

In cathodic protection (CP) technique the corrosion of metal surface is reduced by making the surface cathode of electrochemical cell (entire steel surface is made cathode) by supplying electron from an anode to metal surface. Due to this opposing current local anodes on metal surface are forced to polarise to the potential of local cathode. To measure the cathodic protection level portable devices or permanently embedded probes in the concrete are used. Commonly used embedded reference electrodes are silver or silver chloride. Separate ground connection should be available for reference electrodes to the steel reinforcement. In CP system negative connection to the steel reinforcement for the return path of electric current is required. In CP system chloride ions slowly migrates away from steel reinforcement and towards anode. At steel surface hydroxide ions are produced due to which concrete reverts back to an alkaline state. All these factors are responsible for the arrest of corrosion process with the help of CP technique. It is important to note that the corroded steel reinforcement cannot be restored to its original state but steel reinforcement corrosion in concrete can be effectively stopped by the use of CP technique

It prevents localized as well as uniform corrosion attack on steel. It is very effective in preventing corrosion in tidal zones and intermittently wet surface by seawater. CP technique has proved itself in stopping steel reinforcement corrosion in existing RCC structures, regardless of chloride content in the concrete.

The first application of cathodic protection was carries out by R.F.Stratfull and his associates in the California Department of Transportation on a road bridge (Sly Park) in June'1973. [10] The system continues to function without any physical delamination of the concrete. Electric current is generated during the process of corrosion and to counteract this electric current in CP technique an external source of current is supplied to eliminate the corrosion process.

To extend the service life of RCC bridges CP technique has been used by the Virginia Department of Transportation.

Parameters which should be considered while evaluating an structure are:-

1) Structure choosen should have service life more than ten years
2) Spalling and delamination should be less than fifty percentage of structural area
3) Chloride content should be greater than 0.025% by wt. of concrete
4) Value of half-cell potential should be greater than -200mV
5) Majority of steel rebar should be electrically continous
6) The structure to be protected should be structurally sound

Depending upon the type of anode used the cathodic protection is classified in two categories:-

1) Sacrificial anode cathodic protection (SACP) system
2) Impressed current cathodic protection (ICCP) system

2.7.2.1.1 Sacrificial anode cathodic protection (SACP) system

In this method a metal (anode) which is more electronegative than steel/iron is fixed to the steel surface or continuously wet concrete surface so that electrons pass to the steel surface and in the process the anode is consumed (sacrifices itself) i.e. anodes corrode instead of steel of structure. The metals which are more electro-negative than the metal to be protected in this case steel or iron are used as anode, for example:- zinc, magnesium or aluminum.

In SACP system, movement of electron is from anodic area to cathodic area due to which anodes corrode more quickly and need to be changed at regular interval of time. A SACP system for steel reinforcement in concrete uses more reactive metal as anode like zinc or aluminum zinc indium to create current flow. The relative position of different metals in galvanic series leads to dissimilar metal corrosion, which is the principle of SACP system. Due to the potential difference between anode and the steel reinforcement a direct current is generated when connected. This method is called sacrificial anode because in the protection process the anode gets consumed i.e. sacrificed. From anode the current will flow through concrete to the corroding steel reinforcement in concrete. Anodes can be casted in the concrete or sprayed on the surface of concrete to form sacrificial coating on RCC structures.

SACP system advantage is that it doesn't require external power supply. This technique can be used for pre-stressed or post tensioned concrete. The anode life is short in SACP system than the inert anode used in ICCP system. Disadvantage of this method is that the current output of anode cannot be adjusted or controlled.

Although the application of cathodic protection system for rehabilitation of corroding RCC structures such as bridges and buildings has been in practice in many other countries [8], the same in India has been scarce. Also, not all the case studies are reported / published. It was reported that zinc ribbon based SACP was employed in HPCL refinery in Mumbai [9]. Rajendran and Murugesan reported the application of zinc anode, encased in alkali-activated cement matrix, for repair of corrosion affected jetties in Chennai and Andaman Nicobar Islands [16].

2.7.2.1.2 Impressed Current Cathodic Protection (ICCP) System

A second method of CP technique is called impressed current cathodic protection (ICCP) system. Alternative source of direct current through an external inert anode is supplied to the steel reinforcement surface in this method. The negative terminal of the current source is connected to the steel surface and positive terminal is connected to an external inert anode to complete the electrical circuit. Unlike SACP system, in an ICCP system, the auxiliary anode is not consumed. Basic components required in ICCP system are:-

1) Rectifier (for DC power supply)
2) Inert anode (titanium anode mesh)
3) Conduit and wires
4) Embedded reference electrodes (silver/silver-chloride)

Test results of ICCP system proves that service life of existing structures can be exceeded by forty years and over hundred years for new RCC structures. Although it was used in many countries but no incidences of use of ICCP system in India has been reported or published.

2.7.2.2 Electrochemical Chloride Extraction (ECE) technique

The process of chloride ions removal from concrete by electrochemical technique is known as electrochemical chloride extraction (ECE). This method is also known as chloride extraction (CE) or desalination. The basic principle of ECE technique is similar to that of CP technique to arrest corrosion of steel reinforcement in concrete. The only differences are the level and period of current application. CP system is a permanent installation with current in the region of 5 – 20 mA/m^2 of steel while ECE system is a temporary installation with much higher current density in the range of 0.5 – 2.0 A/m^2 of steel is applied for few weeks. In ECE technique chloride ions migrate towards concrete surface where they are removed. The chloride ions migrate to the concrete surface where they are removed.

This method of chloride extraction or desalination was developed in Kansas Department of Transportation (KDOT) in 1973 experiments on electro stabilization of clayey soils.[18] After that many studies has shown the possibility of removing chloride from concrete using ECE technique.[19-22] For the treatment of vertical surfaces a commercial ECE technique was developed called Norcure^{TM}.[23] The advantage of ECE technique to remove chloride ions is that the contaminated structurally sound concrete will not be removed after the application of chloride ions removal process.

2.7.2.3 Electrochemical Re-alkalization

Electrochemical re-alkalization is a technique in which the alkalinity of concrete is restored. This process is used for carbonated RCC structures. In this method the alkali ions are electrically pushed toward the steel reinforcement, due to which hydroxyl ions are produced at the steel, repassivating the steel and corrosion activity is reduced to a negligeable level. A highly alkaline electrolyte is drawn into the carbonated cover concrete by a process called electro osmosis.

2.8 Observations from literature survey

From the literature survey it has been observed that cathodic protection (CP) is the best technique to prevent steel reinforcement corrosion in RCC structures. It has also been observed that sacrificial anode method is more economical than ICCP method. However there have been very few instances of this method being applied and a little understanding of this method is present. Therefore an attempt has been made in this study to familiarize with the sacrificial anode based cathodic protection technique for repair of a corroding reinforced concrete member.

Chapter 3: EXPERIMENTAL INVESTIGATION

In this chapter the details of an experimental investigation on repair of a corroding reinforced concrete beam member using sacrificial anode (commercially available zinc anode) are presented.

3.1 Experimental Methodology

The experimental methodology consisted of casting an RCC beam member, subjecting it to cyclic wetting and drying process, monitoring of corrosion through OCP Method and removing the delaminated concrete due to corrosion cleaning of corroded reinforcing bar attaching Zinc anodes and levelling the concrete surface with fresh concrete and further monitoring the steel corrosion with OCP method

Due to corrosion stains and cracks were visually observed on the RCC member. Measurement of corrosion potential was taken with the help of a potential measuring instrument. The magnitude of the potential indicates the condition of the steel with respect to corrosion.

3.2.Experimental Details

3.2.1 Material used

3.2.1.1 Concrete

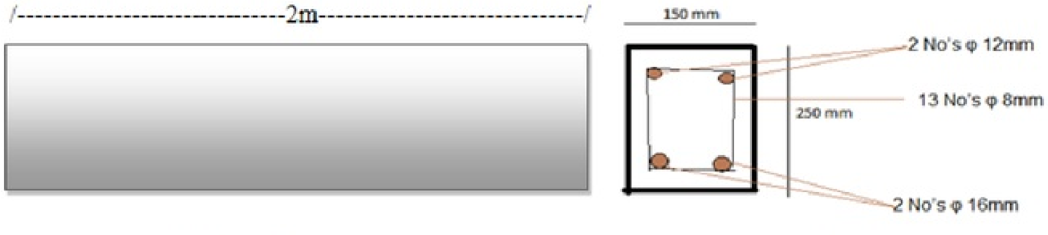
Concrete of strength grade of M-35 was used to cast the RCC beam member. 43 grade OPC was used for the mix   locally available aggregates were used

3.2.1.2 Steel

Tata steel Fe 500 bar conforming to IS: 1786 was used as reinforcing steel for the beam member.

3.2.1.3 Details of the concrete beam member

An   RCC beam of size 150 x 250 x 2000 mm was cast.A schematic diagram of the beam with details of reinforcement bar is shown in Figure 7(a & b). The total surface area of steel used in RCC beam member is 0.56m^2.



(a) R.C.C Beam

(b) Cross-section of beam

Figure 7: - Schematic drawing of R.C.C. Beam

The   beam was first cured for 28 days, following which it was subjected to weekly exposure cycles to 3% of NaCl solution by ponding method (Fig. 8). Corrosion cracks were observed and spalling of concrete was seen at some places on the beam after about three years of exposure (Fig. 9).

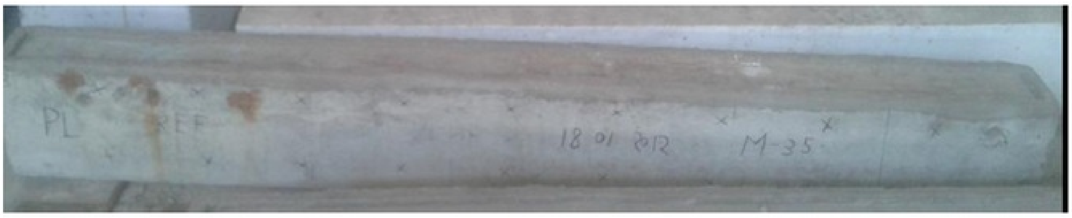


Figure 8: - Beam member before repairing

Figure 9: - Cracks on beam due to corrosion of steel

3.2.2 Repair of RCC Beam using sacrificial anode method

To repair a deteriorated concrete member, the cracked concrete is removed and reinforcing steel is exposed and cleaned. Chemicals can be used if cleaning of rust is to be done more effectively The extent of removal of damaged, defective or porous, deteriorated concrete should be till the rebar is fully exposed and all the loose concrete is removed. It is not a good practice to remove deteriorated concrete only up to the plane of reinforcement and to have a joint between old and new concrete right at the same location. It is better to expose about three-fourth of rebar diameter and expose the corner bars fully.

Anodes are electrically connected to the exposed reinforcing steel simply by wrapping the tie wires around the exposed rebar and twisting them tight, to ensure electrical connection between the zinc anode and the steel rebar.

Once the anodes are installed the concrete would be placed and it is important to consolidate the concrete around the rebar, anode and the contact surface.

3.2.2.1 Removal of Defective Concrete

The cracked concrete was removed with the help of hammer in accordance with as described in section 3.2.2 (Figure 10)

Figure 10: - Beam after removing the defective concrete

3.2.2.2 Cleaning of rust and grinding of the steel

The surface of the steel bar was tamped with the help of the hammer and cleaned with a wire brush. Rebar is grouded to obtain a plain surface at places where the anode block is to be attached to the rebar, so that proper connection between rebar and anode block is maintained (Figure 11).

Figure 11: - Grinding of the rebar surface to facilitate fixing of Zinc Anode

3.2.2.3 Attaching Zinc Blocks to the Rebar

In this study Zinc metal was used as a sacrificial anode for the protection of steel in concrete from corrosion through SACP method. A Zinc plate of dimensions 500x500x 8mm was purchased from the local market, from which small pieces of 250mmx150mm were cut (Fig. 12) Five such zinc blocks each weighing approximately 35 gm were attached to the cleaned steel bars of corroded RCC beam member. .

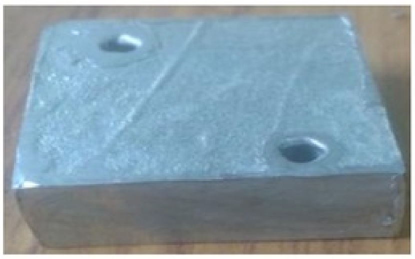


Figure 12: - Zinc Block purchased from the market

The attached zinc blocks to the rebar in patch work of Beam member are shown in Figure 13.

Figure 13: - Attaching Zinc Blocks to the rebars in patch work of Beam member

3.2.2.4 Placing beam in formwork, mixing and pouring of concrete

After fixing the zinc anode blocks at specified position, the beam was placed in a mould (Figure 14) and a 35 MPa grade concrete was used to repair the damaged concrete beam (Figure 15). Proper compaction of the concrete was ensured lthrough vibration.

Figure 14: - Fixing beam in the frame

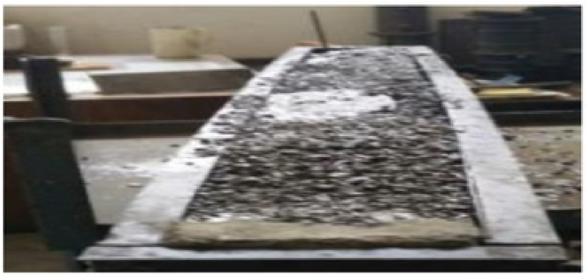


Figure 15: - Pouring of concrete in the frame

3.2.2.5 Removal of formwork and curing of the beam

Figure 16 shows the repaired beam with formwork. Formwork of beam was removed after 48 hours. After removing from the formwork the beam was placed in the curing tank for next 28 days. The repaired beam member after curing is shown in Figure 17.

Figure 16: - Beam before removal of formwork

Figure 17: - Condition of beam after curing for 28 days

3.3 Monitoring of steel reinforcement corrosion through OCP

The steel reinforcement corrosion of the beam was monitored through OCP at Grid points marked on the beam at a spacing of 150 mm vertically and 200 mm horizontally (Figure 18).

Figure 18: Measuring of OCP of reinforcement bar in beam

The test points are schematically shown in Figure 19.

Figure 19: - Grid points on the beam where potential was measured

The criterion recommended in ASTM C-876 was followed to interpret the potential measurements and same is presented in Table 9.

Table 9: Corrosion condition related with half-cell potential (HCP) measurement [17]

S.No.	Open circuit potential (OCP) values (mV vs. CSE)	Corrosion condition
1	> -200	Low (10% risk of corrosion)
2	-200 to -350	Intermediate risk of corrosion
3	-350 to -500	High (90% corrosion risk)
4	< - 500	Severe risk of corrosion

Chapter 4: RESULTS

4.1 Corrosion Potential

The OCP reading of the beam member is shown in Table no. 10. On comparing the values of Table no. 10 to that of Table no. 9 it can be concluded that the most of the steel reinforcement of the beam has severely corroded.

Table 10: Potential of beam member before repairing

(Row 1)	27-05-15	02-06-15	09-06-15	(Row 2)	27-05-15	02-06-15	09-06-15
1	-510	-541	-594	11	-322	-385	-449
2	-486	-510	-558	12	-310	-359	-427
3	-497	-521	-546	13	-304	-361	-427
4	-490	-540	-571	14	-285	-366	-439
5	-475	-514	-563	15	-393	-412	-476
6	-498	-519	-563	16	-349	-410	-474
7	-414	-483	-542	17	-367	-440	-501
8	-401	-490	-536	18	-456	-551	-590
9	-467	-517	-561	19	-418	-546	-578
10	-424	-511	-554	20	-544	-574	-594

After repairing the beam member, the corrosion potential was again measured with the help of OCP method whose values are presented in Table 11.

Table 11: Potential of Beam member after repairing of the beam member

Grid Points (Row 1)	18-12-2015 (After Repair)	Grid Points (Row 2)	18-12-2015 (After Repair)
1	-431	11	-329
2	-488	12	-353
3	-501	13	-400
4	-506	14	-484
5	-532	15	-459
6	-540	16	-489
7	-534	17	-490
8	-369	18	-384
9	-425	19	-423
10	-537	20	-520

A plot of corrosion potential readings with time is shown in Figure 20.

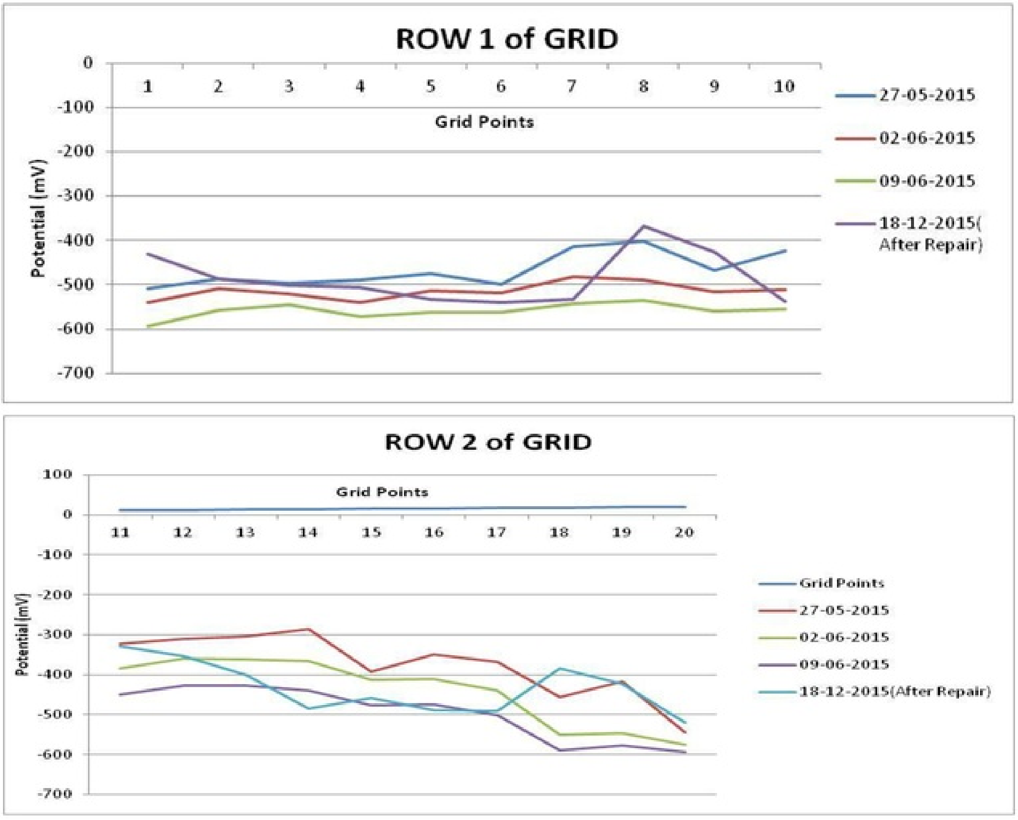


Figure 20: Graphical representation showing variation of potential before and after repairing of beam member.

3.2 Observation

It was observed from the test readings that initially the OCP values moved in the negative direction, indicating progress of corrosion of steel. However after repair, the potential values have started moving in the positive direction indicating reduced corrosion activity which shows that the zinc anodes were able to reduce the steel reinforcement corrosion in concrete. It may be noted that, although the zinc anodes were fixed to that portion of the reinforcement bar, where the effect of corrosion (in the form of cracks on surface of concrete), their effect would be manifested all along the reinforcement bar.

4.3 Concluding Remarks

Adequate concrete cover over reinforcement is essential for a durable structure. The concrete cover required for a durability purpose has been recommended in IRC: 112 [11]. However, it is often observed that concrete cover being provided in structures is much less than that required due to construction inadequacies. The author's experience with testing of bridges and buildings revealed that, the buildings are the most neglected as far as providing adequate concrete cover is concerned [12]. Such structures suffer from early deterioration due to corrosion of steel either due to carbonation or chloride attack, and the same can be repaired satisfactorily by the use of SACP system, as discussed in the paper. The cracked concrete is removed, the corroding reinforcement bar is cleaned and adequate no. of zinc anodes are fixed, and the concrete is patch repaired. As the thickness of the zinc anode unit or zinc anode metal piece used in this is only a few mm., it may be inferred that such a system could be useful to reduce the on-going steel reinforcement corrosion in concrete structures where concrete cover is less and cannot be increased due to construction related problems, and application of ICCP to such structures is economically not viable.

Chapter 5: CONCLUSION

From the recorded values of potential shown in Table no. 8 and 9 it is observed that after installing zinc anode in the beam member the corrosion of reinforcement in the beam has reduced.

The conclusions drawn from this report are:-

1) Cathodic protection technique is a better method to repair corroding concrete structures compared to conventional repair to prevent the formation of incipient anodes.
2) Sacrificial anode cathodic protection can be used in structures with less concrete cover.
3) An attempt was made to familiarize with the SACP system which showed that a small zinc metal piece when attached to corroding steel could reduce the corrosion and can be easily adopted for repair of concrete structures

Summary

SACP method is used to provide a convenient, cost effective corrosion control for reinforced cement concrete structures. Applications of SACP system includes patch repair and protection against localised corrosion and joints between existing and new concrete. This system is also used in distributed corrosion protection by providing blanket corrosion protection to entire structure exposed to corrosive environment. Zinc anode provides the desired level of corrosion protection system without creating any additional corrosion concern for the structure.

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