“CATHODIC PROTECTION OF CORRODED PRESTRESSING TENDON BY CFRP SHEETS”

A thesis submitted in partial fulfilment
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IN
STRUCTURES

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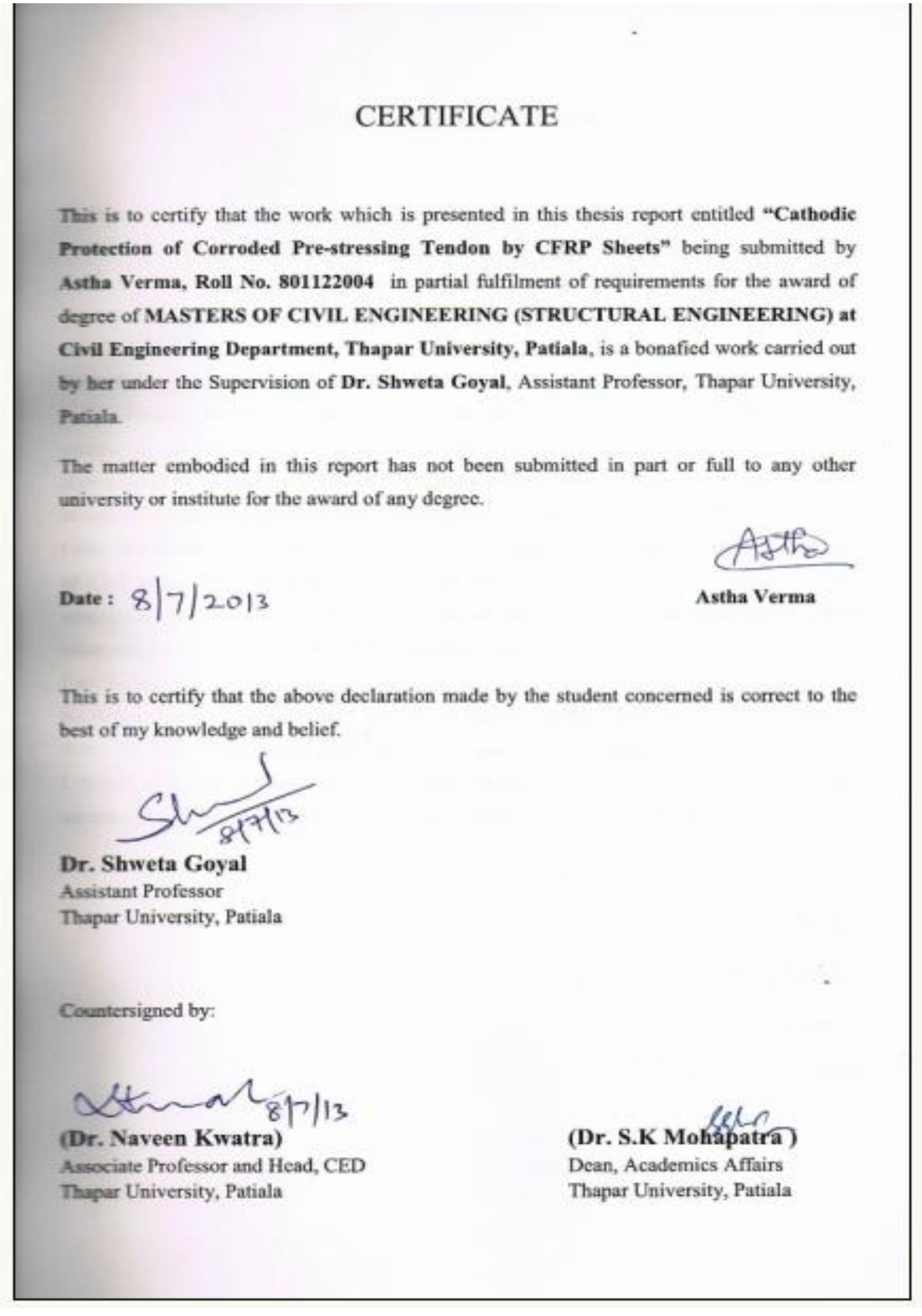

CERTIFICATE

This is to certify that the work which is presented in this thesis report entitled **"Cathodic Protection of Corroded Pre-stressing Tendon by CFRP Sheets"** being submitted by **Astha Verma, Roll No. 801122004** in partial fulfilment of requirements for the award of degree of **MASTERS OF CIVIL ENGINEERING (STRUCTURAL ENGINEERING) at Civil Engineering Department, Thapar University, Patiala**, is a bonafied work carried out by her under the Supervision of **Dr. Shweta Goyal**, Assistant Professor, Thapar University, Patiala.

The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

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Date : 8/7/2013

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This is to certify that the above declaration made by the student concerned is correct to the best of my knowledge and belief.

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ABSTRACT

Reinforced concrete is one of the most commonly used construction materials in civil engineering but its durability problems have been obsessing people. The worst of these problems is caused by corrosion of steel in concrete, inducing the early deterioration of concrete infrastructures. Structural deterioration of reinforced concrete structures affected by corrosion is a gradual process consisting of a few different phases during service life, including corrosion initiation, concrete cracking, excessive deflection and final collapse due to loss of structural strength.

Cathodic Protection is a reduction or elimination of corrosion by making the metal a cathode by impressing a DC current. A new development in repair and rehabilitation of RC structures is the use of carbon fiber reinforced polymers (CFRP) which provide a barrier layer that is expected to impede further corrosion of steel and prevents dislodging of concrete cover. Another important advantage of CFRP could be active protection of structures using CFRP wraps as anode and the steel rebar as cathode.

The present work investigates protection of the strand achieved by using surface bonded carbon FRP. The electrically conductive carbon fibre is used as anode while the prestressing tendon is used as cathode in the present active protection. To initiate initial corrosion in the specimens, impressed current was passed through the strand. Then, carbon FRP sheets have been adhesively bonded by using conductive epoxy to the block specimens. Specimens were exposed to highly corrosive environment for specified time. It is observed that the active protection technique is very effective in retarding the corrosion of strand.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Reinforced concrete (RC) has been developed and applied extensively in the twentieth century and it continues to be used in this century as well. It combines the good compressive strength of concrete with the tensile strength of steel and has proven to be successful in terms of both structural performance and durability. It is an extremely popular construction material. Because of the nature and role of concrete in the creation, rehabilitation and regeneration of the infrastructure system of any country, RC plays a very important part in a nation’s economic development. Lack of durability of RC structures not only has massive economic implications to a nation’s well-being, but it is also one of the greatest threats to sustainable growth of concrete and construction industries. However, one major flaw, namely its susceptibility to environmental attack, can severely reduce the strength and life of these structures.

Corrosion is defined as the destruction or deterioration of a material because of its reaction with environment. When metals revert to their combined state, they are said to have corroded. Corrosion may affect one or more properties of the metal, which need to be preserved. In case of corrosion of iron and steel, iron oxidizes into iron oxides. These oxides are usually weaker than steel. They are loosely attached and spall off from the surface. This leads to reduction in strength and reliability of structures. Also the resulting corrosion products occupy volumes several times that of the steel. The increased volume induces tensile stresses in the concrete that result in cracking, delamination and spalling of concrete. As a result, the reinforcements get exposed to direct environmental attack and the corrosion is accelerated. The typical corrosion of R.C Structures is shown in **Fig. 1.1**.

Although corrosion of steel may not immediately affect the integrity and the ultimate load carrying capacity of a RC structural member, it is the most complex, insidious and destructive form of damage. Once it starts, it is almost impossible to stop the process until eventually the safety, stability and design service life are all drastically reduced with time.

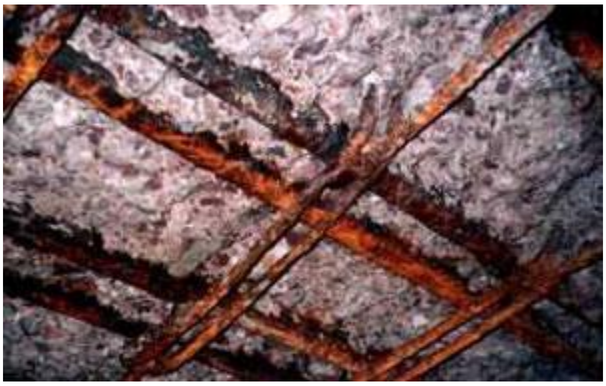


Fig. 1.1 Corrosion in R.C Structure (Gadve et al., 2008)

1.2 CORROSION MONITORING IN R.C STRUCTURES

Repair of corrosion affected structures is often difficult, expensive, hazardous and disruptive to the operations of the building and structures. This repair is required when the structure has lost its load carrying capacity. This process takes lot of time and if proper action is taken well in advance, then the costly repairs can be avoided. This is possible if the structures are monitored regularly. Therefore, there is a critical need for monitoring of R.C Structures by the use of new and emerging materials and technologies that will facilitate the functionality and efficiency, along with increasing the overall durability and life span of the structures.

Corrosion monitoring gives a complete picture of the changing condition of a structure with time and there are several methods of monitoring the corrosion of steel reinforcement in concrete. In the last few decades, a number of damage detection techniques such as Destructive and Non-Destructive techniques have been developed to analyse changes in structure due to corrosion. Destructive techniques result in accurate measurements and gives specific characteristics of materials by destroying the specimen. Pullout strength, mass loss and compression test are some examples of destructive testing. Non-destructive techniques, on the other hand, monitor the material quality without destroying the specimen. The inspection ability of these systems is very limited and extremely costly. Therefore, in many areas of modern engineering, non-destructive evaluation (NDE) techniques have provided valuable and often critical information for the safe operation of the most complex systems. Such usefulness has recently been greatly enhanced by the tremendous advances in computer and communication tools.

The more common of these methods are the half cell potential, linear polarization resistance and AC impedance. The half cell potential method only predicts the probability of corrosion activity whereas linear polarization resistance and AC impedance are capable of measuring the corrosion rate that occurs in a system (*Raharinaivo et. al (1986), Bonacci & Maleej (2000), Bertolinia et. al (2004)).*Various techniques for measuring the corrosion rate have been used to detect the corrosion at an early stage, in order to predict residual lives and accordingly decide what preventive or repair systems are to be applied (*Song and Saraswathy, 2007*). New RC structures incorporating one or more of these new strategies are likely to have much longer durable service life than those constructed before.

.

The various non–destructive techniques to monitor corrosion in reinforced concrete structures are given below which are discussed in detail in Chapter 2 (*Song and Saraswathy, 2007*):-

- Half Cell Potential Measurements
- Linear Polarization Resistance Method
- Ultrasonic Pulse velocity Method
- Open Circuit Potential Measurements
- Surface Potential Measurements
- Electrochemical Impedance Spectroscopy
- Acoustic Emission
- Impact-echo Method
- Infrared Thermography

1.3 MAJOR CORROSION PROTECTION METHODS

There are various methods which has been discussed below to protect R.C structures against Corrosion. Following are the methods:-

1.3.1 Inorganic/Metal Coatings or Organic/Paint Systems

Organic coatings are effectively applied for the corrosion protection of metals, due partly to the role they play as a physical barrier between the metal surface and the corrosive environment. However, all polymers are osmotic to potentially corrosive species such as oxygen, water and ions. The coatings that are investigated by various authors involve alkyd, epoxy polyamide and polyester polymeric films *(S.D. Cramer, B.S. Covino, Jr., G.R. Holcomb, S.J. Bullard, W.K. Collins, R.D. Govier, R.D. Wilson, and H.M. Laylor* **,** *(1988))*

1.3.2 Inhibitors

Corrosion inhibitors are a class of protective products that are added to the concrete mix to delay and prevent corrosion. As such, they are considered admixtures. Both organic and inorganic inhibitors are commercially available. Calcium nitrite is an inorganic inhibitor and is the most extensively tested corrosion-inhibitive admixture since it was introduced during the 1970's.

According to their action, the inhibitors can be classified into three groups:

- **Anodic inhibitors** these inhibitors prevent the reinforcement corrosion by affecting the anodic process. Most widely used compounds that belong to this group are nitrites and chromates. If the anodic inhibitor is not present in sufficient concentration on the complete reinforcement surface, pitting corrosion can appear, creating local damage, which can be more dangerous than no inhibitor at all; this can happen with improper blending of concrete mix.
- **Cathodic inhibitors** these inhibitors are adsorbed on the reinforcement surface and create a barrier of molecular thickness, thus enhancing the kinetics of the electrode reactions. Examples of compounds that are cathodic inhibitors include various amines. The initial adsorption of a cathodic inhibitor on the reinforcement surface is influenced by the electrochemical attraction forces between the steel surface and the inhibitor. Cathodic inhibitors do not enhance localized attack, even when concentration drops below the critical level, which is their basic advantage.
- **Mixed inhibitor** influences both the cathodic and anodic processes. Because of the micro cell corrosion processes occurring in reinforced concrete, a mixed inhibitor is ideally suited for application.

1.3.3 Controlling the Electrode Potential

This type of protection can be achieved by:-

- **Anodic Protection**

  Anodic Protection (AP) is a technique to control the corrosion of a metal surface by making it anode of electrochemical cell and controlling the electrode potential in a zone where the metal is passive. Anodic Protection is used to protect metals that exhibit passivation in environments whereby the current density in the freely corroding state is significantly higher than the current density in the passive state over a wide range of potentials. Anodic Protection is used for carbon steel storage tanks containing extreme low pH environments including concentrated sulphuric acid (**Fig.1.2**). Anodic Protection is used to protect metals that exhibit 50% caustic soda where cathodic protection is not suitable due to very high current requirements. An Anodic protection system includes an external power supply connected to auxiliary cathodes and controlled by a feedback from reference electrode. Careful design and control is required when using Anodic Protection for several reasons, including excessive current when passivation is lost or unstable, leading to possible accelerated corrosion.

Fig 1.2 Anodic Protection in Carbon Steel Storage tanks

- **Cathodic Protection**

  Corrosion occurs when an electric current (corrosion current) flows from the metal surface into the electrolyte at the anodic areas and onto the metal surface from the electrolyte at the cathodic areas. It is possible to make every part of the metal surface cathodic. This can be done by applying an external current from a power supply using an anode that will not easily corrode (impressed current cathodic protection), or by using a material that is electrically more negative to deliberately create a galvanic corrosion cell where all the corrosion takes place on a piece of metal (sacrificial anode) that is not structurally significant.

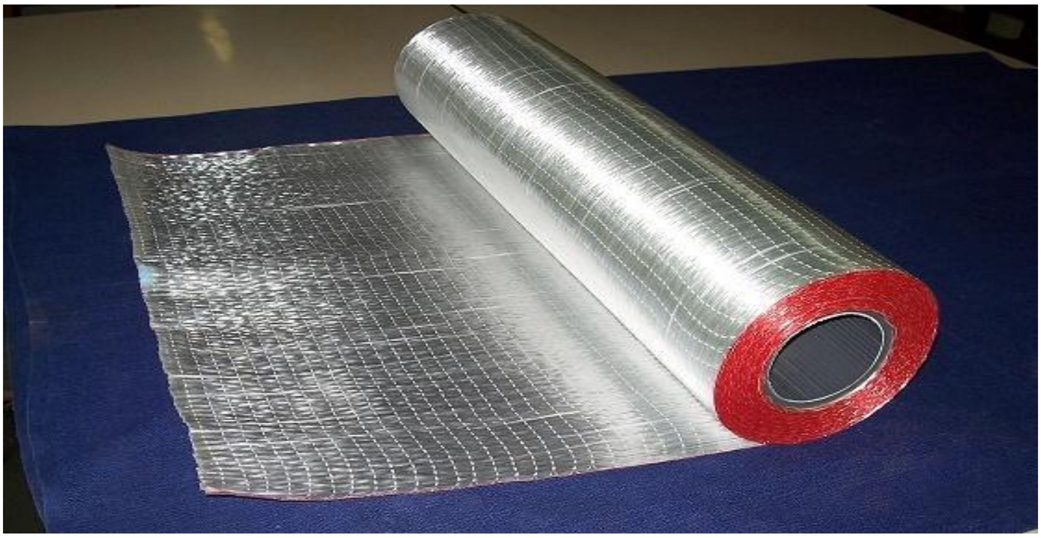
  In practice, the direct current is forced to flow from a source, external to the metal surface, onto all the metal surfaces. When the amount of current is properly adjusted, it will overcome corrosion current discharging from all the anodic areas on the metal and there will be a net current flow onto the protected surface at these points. The entire steel surface will then be cathodic and full protection is achieved. Similar method is used in the present study to protect prestressing tendons from corrosion.

1.4 FIBRE REINFORCED PLASTIC (FRP)

Recent developments in the field of FRP have resulted in the development of one another highly efficient construction materials. They have been successfully used in a variety of industries such as aerospace, automobile and shipbuilding. The FRPs are unaffected by electrochemical and electro-mechanical deterioration and can resist corrosive effects of acids, alkalis, salts and similar aggregates under a wide range of temperatures. FRP thus hold a very distinct advantage over steel plates as an external reinforcing device. Moreover, FRP are available in the form of laminas and different thickness and orientation can be given to different layers to tailor its strength according to specific requirements.

The FRP sheets are being used for repair, strengthening and retrofitting of structural components due to their low weight, ease of handling and rapid implementation. Also FRP wrapped samples have shown substantially higher resistance to corrosion (*Gadve et. al (2008), Bonacci & Maleej (2000), Debaiky et. al (2002)*).

Glass fibre reinforced plastic (GFRP) and Carbon fibre reinforced polymers (CFRP) sheets have been extensively used in today's world for retrofitting of existing structures. These are usually bonded to the surface of the concrete structure and are utilized to strengthen existing structures or rehabilitate structures damaged by corrosion. **Fig 1.3** shows typical view of Fibre reinforced plastic sheet.



.**Fig. 1.3 Fibre Reinforced Plastic Sheet**

1.5 ORGANISATION OF WORK

- **Chapter 1** discuss general introduction of corrosion and the need of various monitoring techniques and various protection methods and use of FRP to rehabilitate the concrete structures.
- **Chapter 2** explain in detail the Electro Chemistry involved in Corrosion process and also gives brief description on different types of corrosion and discuss various techniques used for monitoring of RC structures.
- **Chapter 3** deals with Cathodic Protection, its principles and its advantages and disadvantages.
- **Chapter 4** deals with FRPs and monitoring of retrofitted elements. In this, various types of FRPs, their advantages and suitability have been

discussed. Also the need for monitoring of retrofitted elements has been mentioned.

- **Chapter 5** presents a thorough literature review on monitoring techniques for monitoring rebar corrosion in concrete. Also a thorough review of literature on Fibre Reinforced Plastic (FRP) composite wraps for corrosion protection is also presented.
- **Chapter 6** represents the experimental programme, wherein all test procedures and measures to be followed during experiments are explained in detail.
- **Chapter 7** deals with results and discussions where findings of the experimental programme are explained in detail.
- **Chapter 8** is the concluding chapter. This chapter is followed by the list of references used in the present study.

CHAPTER 2

ELECTRO CHEMISTRY OF CORROSION PROCESS

2.1 INTRODUCTION

In this chapter, the basic mechanisms of corrosion have been discussed. For the present work, it is important to understand corrosion of steel not only in isolation but also as a component of a RC system. A discussion on corrosion in reinforced concrete has been included in this chapter.

2.2 CORROSION MECHANISM

The corrosion of steel reinforcing bars is an electrochemical process that requires a flow of electric current and several chemical reactions. The three essentia1 components of a galvanic corrosion cell are anode, cathode, and electrolyte.

At the anode, iron is oxidized to the ferrous state and releases electrons:

$$Fe \rightarrow Fe^{++} + 2e^{-} \qquad (2.1)$$

These electrons migrate to the cathode where they combine with water and oxygen to form hydroxyl ions:

$$2e + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^{-} \qquad (2.2)$$

The hydroxyl ions combine with the ferrous ions to form ferrous hydroxide ($Fe[OH]_2$):

$$Fe^{++} + 2OH^{-} \rightarrow Fe\,(OH)_2 \qquad (2.3)$$

In the presence of water and oxygen, the $Fe\,(OH)_2$ is oxidized further to form ferric oxide (Fe_2O_3):

$$4Fe\,(OH)_2 + O_2 + H_2O \rightarrow 4Fe\,(OH)_3 \qquad (2.4)$$

$$2Fe\,(OH)_3 \rightarrow Fe_2O_3.2H_2O \qquad (2.5)$$

It can be concluded from equation **(2.5)** that the Ferric oxide so formed as a result of corrosion causes the rebar to swell about 2-3 times more than volume of original rebar.

Corrosion of steel in concrete in the presence of chlorides, but with no oxygen (at the anode), takes place in several steps. **Fig. 2.1** shows electrochemical nature of corrosion process in chloride environment

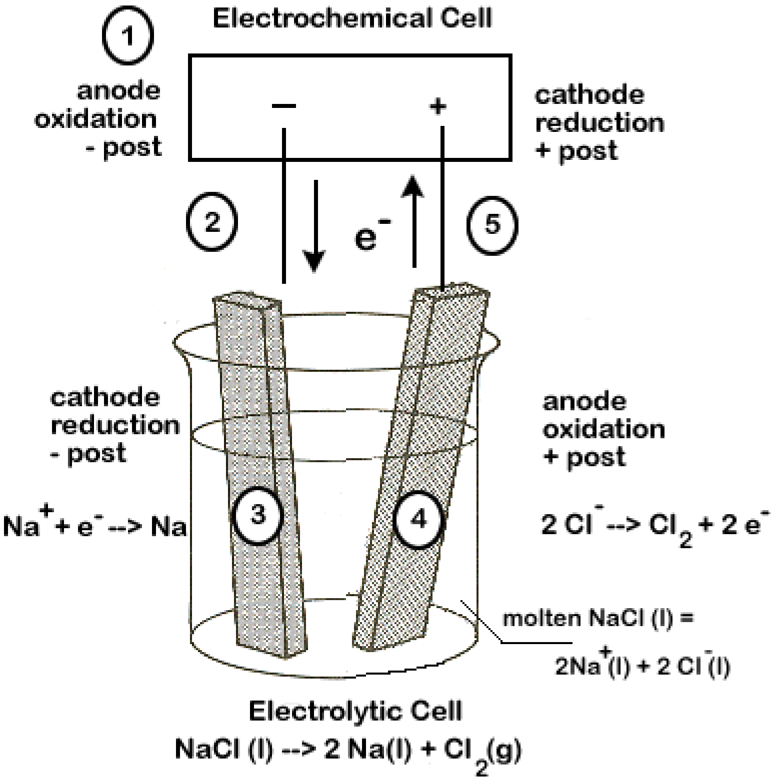


Fig. 2.1 Electrochemical nature of corrosion process in chloride environment

At the anode, iron reacts with chloride ions to form an intermediate soluble iron-chloride complex ($Fe^{++} + 2Cl^{-)}$

When the iron-chloride complex diffuses away from the bar to an area with higher pH and concentration of oxygen, it reacts with hydroxyl ions to form $Fe(OH)_2$.

$(Fe^{++} + 2Cl^{-)} + 2H2O + 2e^{-} \rightarrow Fe\ (OH)_2 + 2H^{+} + 2Cl$ (2.6)

The hydrogen ions then combine with electrons to form hydrogen gas:

$$2H^{+} + 2e^{-} \rightarrow H_2 \quad (2.7)$$

As in the case of corrosion of steel without chlorides, the $Fe(OH)_2$, in the presence of water and oxygen, is oxidized further to form Fe_2O_3:

$$4Fe\ (OH)_2 + O_2 + H_2O \rightarrow 4Fe(OH)_3 \quad (2.8)$$

$$2Fe\ (OH)_3 \rightarrow Fe_2O_3.2H_2O \quad (2.9)$$

As can be seen from Equation **(2.5)** and **(2.9),** the end product so formed in both the corrosive process is Fe_2O_3 which causes the rebar of any concrete structure to swell or occupies larger volume about 2-3 times more than the original volume of rebar and causes internal stresses inside the concrete, causing spalling of concrete Structures. **Fig. 2.2** represents corrosion cell in reinforced concrete.

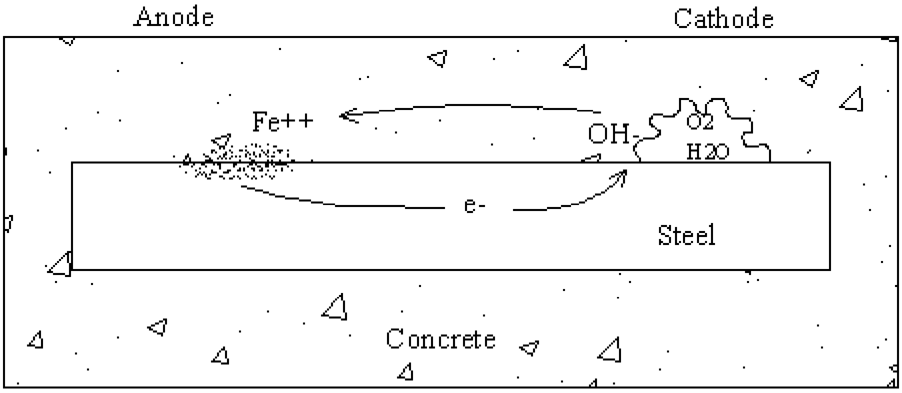


Fig. 2.2 Corrosion Cell in Reinforced Concrete (Gadve et al. 2010)

Both the anodic and cathodic reactions are necessary for the corrosion process to occur and they need to take place simultaneously. The anode and cathode can be located next to each other or can be separated. When they are located next to each other, i.e., on microscopic scale, the resulting corrosion cell is referred to as a microcell. When they are separated by some finite distance, the resulting corrosion cell is referred to as macro cell as illustrated in **Fig 2.3** Corrosion of steel reinforcing bars embedded in concrete may be due to a combination of macro cells and microcells.

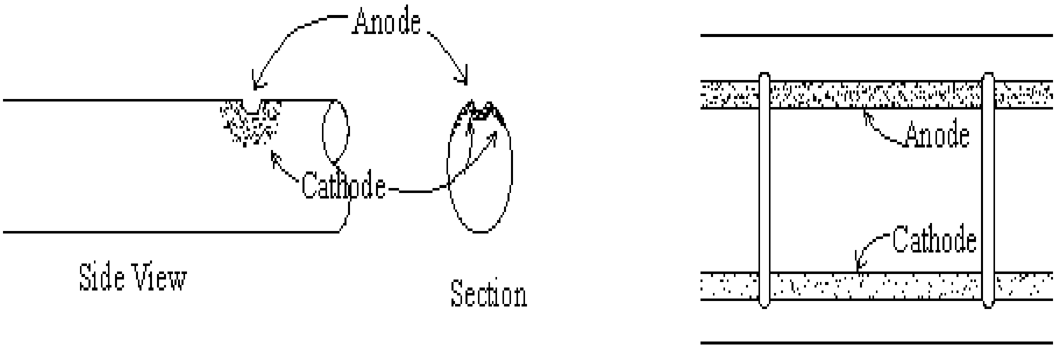


Fig. 2.3 Micro cell and Macro Cell (Gadve et al. 2010).

2.3 DIFFERENT TYPES OF CORROSION

The various forms of corrosion:-

- **Pitting Corrosion**

Pitting corrosion is one of the most destructive and intense forms of corrosion. It can occur in any metal but is most common on metals that form protective oxide films, such as aluminium and magnesium alloys. It is first noticeable as a white or gray powdery deposit, similar to dust, which blotches the surface. When the deposit is cleaned away, tiny holes or pits can be seen in the surface. These small surface openings may penetrate deeply into structural members and cause damage completely out of proportion to its surface appearance. **Fig.2.4** shows the typical view of metal undergoing Pitting Corrosion. In R.C structures, this form of corrosion is typical in chloride induced corrosion.

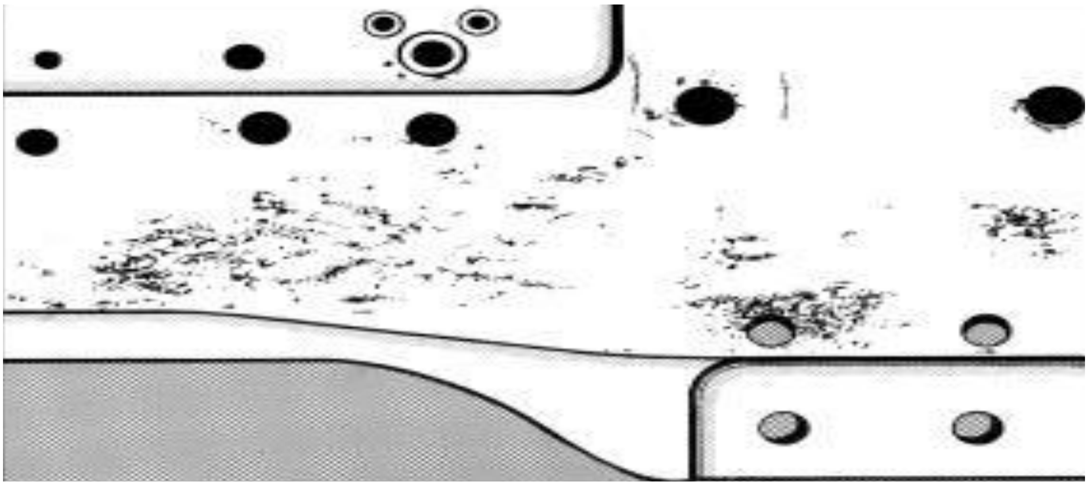


Fig 2.4 Pitting Corrosion (external view)

- **General Surface Corrosion**

General surface corrosion (also referred to as Uniform Etch or Uniform Attack corrosion) is the most common form of corrosion and results from a direct chemical attack on a metal surface and involves only the metal surface. **Fig 2.5** illustrates typical General surface corrosion. General surface corrosion usually occurs over a wide area and is more or less equal in dispersion. On a polished surface, this type of corrosion is first seen as a general dulling of the surface, and if allowed to continue, the surface becomes rough and possibly frosted in appearance. The discoloration or general dulling of metal created by exposure to elevated temperatures is not to be considered general surface corrosion. During Carbonation induced corrosion of R.C Structures general surface corrosion is predominant.

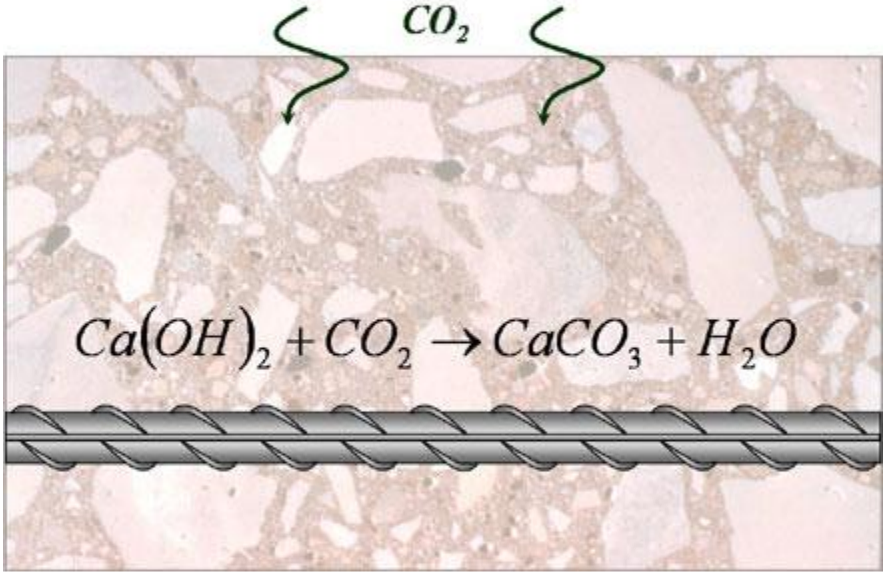


Fig. 2.5 General Surface Corrosion

- **Concentration Cell Corrosion**

Concentration cell corrosion, (also known as Crevice Corrosion) is corrosion of metals in a metal-to-metal joint, corrosion at the edge of a joint even though the joined metals are identical, or corrosion of a spot on the metal surface covered by a foreign material. **Fig 2.6** shows typical view of cell corrosion in metals. This type of corrosion occurs at the contact of two metals only, so is not possible in R.C structures.

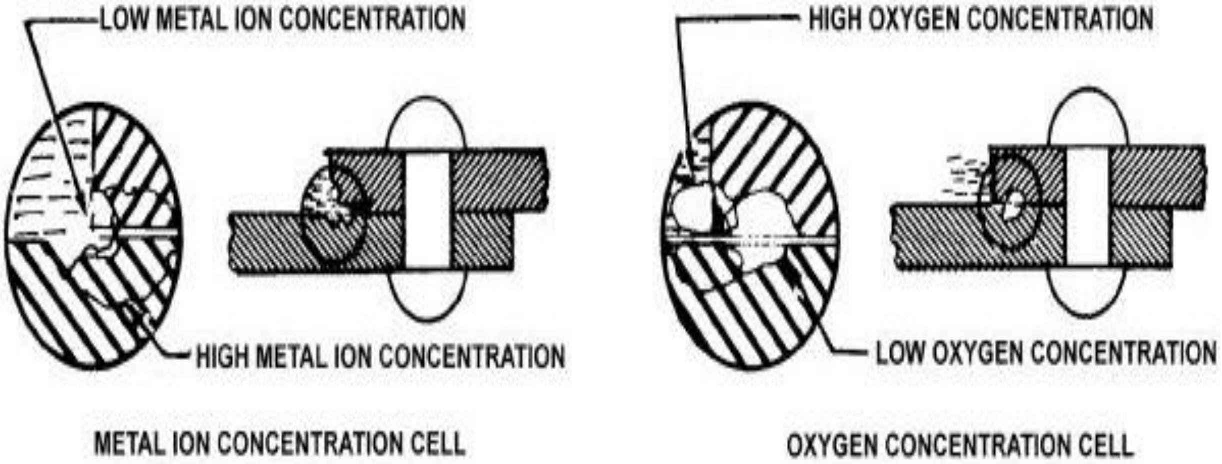


Fig. 2.6 Concentration Cell Corrosion

- **Active-Passive Cells**

Metals which depend on a tightly adhering passive film, usually an oxide, for corrosion protection are prone to rapid corrosive attack by active-passive cells. Active-passive cells are often referred to as a type of concentration cell corrosion. However, the active-passive cell is actually two forms of corrosion working in conjunction. The corrosive action usually starts as an oxygen concentration cell. As an example, salt deposits on the metal surface in the presence of water containing oxygen can create the oxygen cell. The passive film will be broken beneath the salt crystals. Once the passive film is broken, the active metal beneath the film will be exposed to corrosive attack. Rapid pitting of the active metal will result. This reaction can become locally intense due to several factors. First the reaction is augmented by the affected area, since the proportion of the exposed base metal is small compared to the surrounding nonreactive metal. This effectively concentrates the focal point of the reaction, often resulting in deep pits in a short time and a greater rate of corrosion.**Fig.2.7** shows the typical view of Active Passive cell corrosion. This type of corrosion is one form of pitting corrosion only.

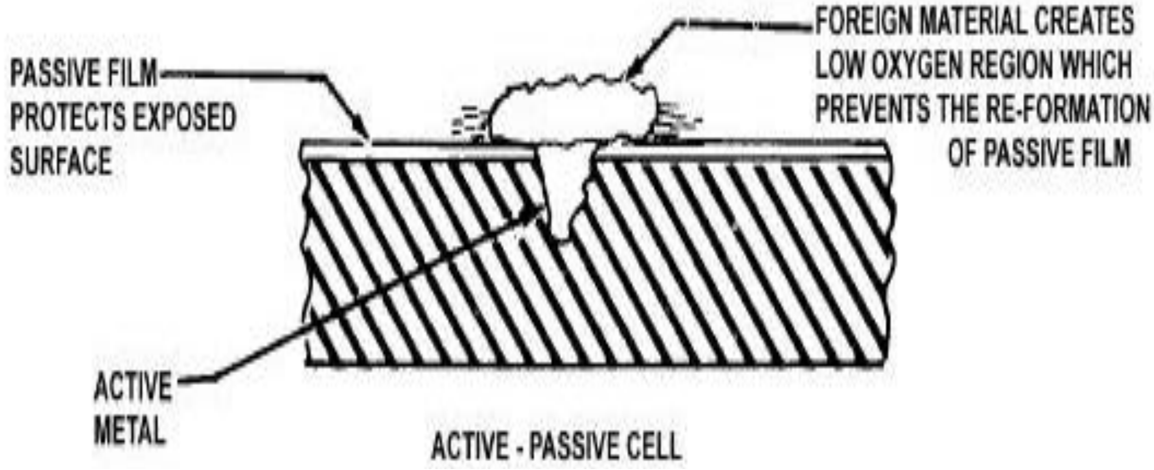


Fig. 2.7 Active Passive Cell

- **Filiform Corrosion**

Filiform corrosion is a special form of oxygen concentration cell which occurs on metal surfaces having an organic coating system. It is recognized by its characteristic worm-like trace of corrosion products beneath the paint film. Polyurethane finishes are especially susceptible to filiform corrosion. Filiform occurs when the relative humidity of the air is between 78 and 90 percent and the surface is slightly acidic. This corrosion usually attacks steel and aluminium surfaces. It occurs on the rebar's lying in open air before they are put in R.C elements. If the corrosion is not removed, the area treated, and a protective finish applied, the corrosion can lead to inter granular corrosion, especially around fasteners and at seams. Filiform corrosion can be removed using glass bead blasting material with portable abrasive blasting equipment or sanding.

- **Stress Corrosion Cracking**

This form of corrosion involves constant or cyclic stress, acting in conjunction with a damaging chemical environment. **Fig 2.8** shows typical view of Stress Corrosion Cracking. The stress may be caused by internal or external loading.

Internal stress may be trapped in a part of structure during manufacturing processes such as cold working or by unequal cooling from high temperatures. Most manufacturers follow up these processes with a stress relief operation. Even so, sometimes stress remains trapped. The stress may be externally introduced by riveting, welding, bolting, clamping, press fit, etc. If a slight mismatch occurs, or a fastener is over-torque, internal stress will be present.

R.C structures are meant to be subjected to extend loads, thus cracks are always there in concrete cover. These small cracks can help the aggressive ions to reach rebar surface and hence accelerates the corrosion process.

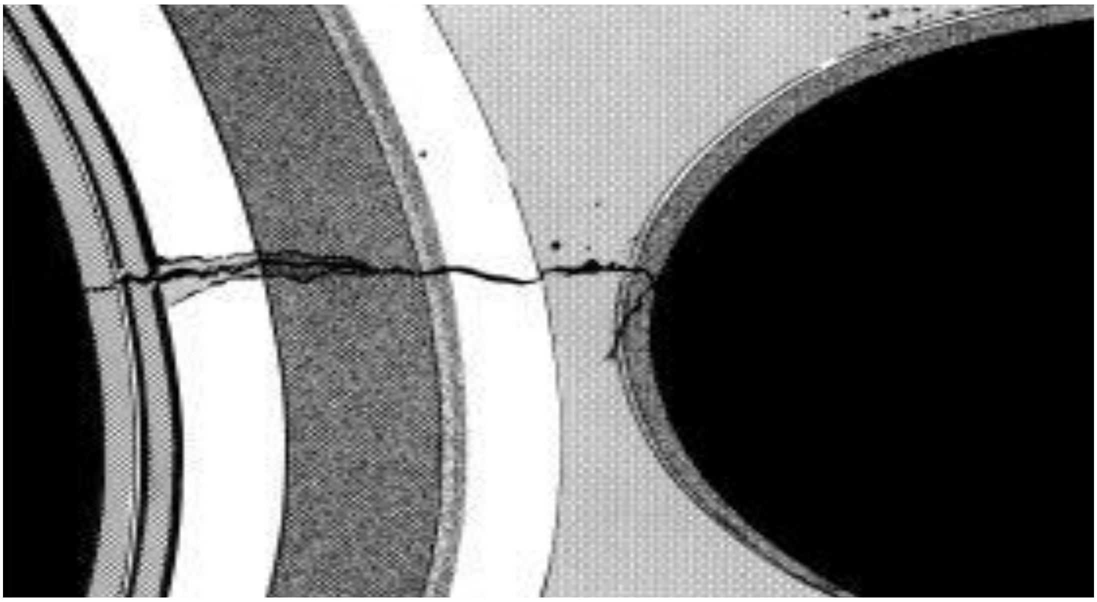


Fig. 2.8 Stress Corrosion Cracking

2.4 MONITORING OF CORROSION

Monitoring of Reinforced Concrete Structure is necessary to know the present condition of structure and to protect it from any future damage. Concrete structures that are subjected to repeated service loads, weathering or chemical attack may display surface-breaking cracks. These cracks may eventually lead to failure of the structure as they extend from the surface into the material, or take a role in the corrosion of reinforcement in concrete (*Broomfield, 2006*). It is therefore essential to be able to assess the condition of concrete structures, and more specifically, to estimate the depth of surface breaking cracks. Non-destructive techniques (NDT) are suitable candidates to reach this goal as compared to partially destructive tests because they allow for in-situ inspection with high spatial resolution, whereas tests performed on drilled cores may only be performed on a limited number of measurement points. Also, NDT will not affect the integrity of structure, as is possible with drilling cores. Various methods of monitoring of R.C Structures are discussed below:-

- **Visual inspection**, which is an essential precursor to any intended non-destructive test. An experienced civil or structural engineer may be able to establish the possible cause(s) of damage to a concrete structure and hence identify which of the various NDT methods available could be most useful for any further investigation of the problem.
- **Half-cell electrical** potential method, used to detect the corrosion potential of reinforcing bars in concrete. In this, the potential of rebar is measured with respect to standard electrode.
- **Linear Polarization Resistance (LPR)**, used to estimate the corrosion rate of steel in concrete. The value of corrosion rate helps in estimating the amount of damage to rebar. Hence estimates the rate at which aggressive environment will reach the rebar surface.
- **Permeability test**, used to measure the flow of water through the concrete. Permeability test measures the ease with which liquid, ions, gases can penetrate into the concrete.
- **Schmidt/rebound hammer test,** used to evaluate the surface hardness of concrete and hence the strength of the surface and near surface layers of the

concrete. It works on the principle that the rebound of an elastic mass depends on the hardness of surface against which the mass impinges.

- **Penetration resistance or Windsor probe test,** used to measure the surface hardness and hence the strength of the surface and near surface layers of the concrete. However, the problem does relate to some property of concrete below the surface.
- **Carbonation depth measurement test**, used to determine whether carbon-di-oxide has reached the depth of the reinforcing bars and hence corrosion may be occurring. The carbonation process is also called depassivation. Carbonation penetrates below the exposed surface of concrete extremely slowly.
- **Radiographic testing** is used to detect voids in the concrete. The beam of radiation, which emerges from the material, is usually used to expose a radiation sensitive film so that different radiation of intensities are revealed as different densities on the film.
- **Ultrasonic pulse velocity testing**, mainly used to measure the sound velocity of concrete and hence the compressive strength of the concrete.
- **Infrared thermography**, used to detect voids, delamination and other anomalies in concrete and also detect water entry points in buildings.
- **Impact echo testing**, used to detect voids, delamination and other anomalies in concrete with one sided access to the structure. The principle is based on measurement of time interval between transmitting an ultrasonic impulse into the structure and receiving an echo.

Method used in present work to monitor specimens for corrosion are discussed in detail in the following section:-

2.4.1 Half-Cell Potential Method

The method of Half-cell potential measurements normally involves measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. The half-cell is usually a copper sulphate or silver chloride cell, or saturated calomel electrode can also be used. The concrete functions as an electrolyte and the risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to a measured potential difference.

ASTM C876-91 gives standard half-cell potentials of uncoated reinforcing steel in concrete.

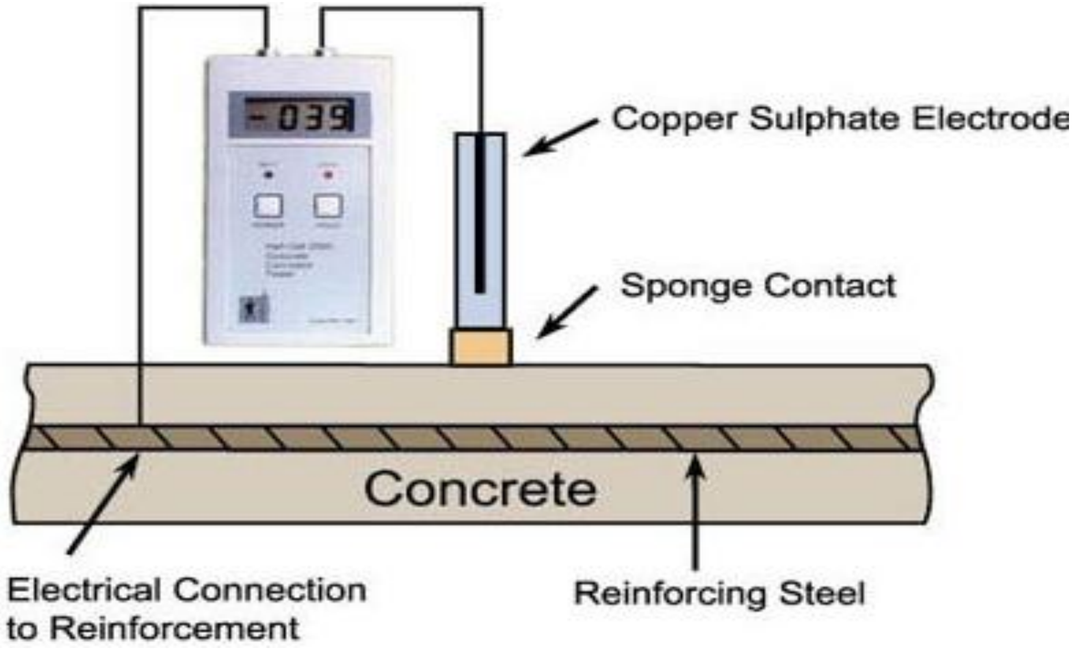


Fig. 2.9 Half-cell potential

The Half-cell consists of a rigid tube or container composed of dielectric material that is non-reactive with copper or copper sulphate, a porous wooden or plastic plug that remains wet by capillary action, and a copper rod that is immersed within the tube in a saturated solution of copper sulphate. The solution is prepared using reagent grade copper sulphate dissolved to saturation in distilled or deionised water. **Fig. 2.9** shows the typical view of Half-Cell Potential. The risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to the measured potential difference by the half cell equipment.

Measurements are made in either a grid or random pattern. A direct low resistance electrical connection is made to the pre-exposed reinforcing steel with a compression clamp or by brazing or welding a protruding rod. The bar is connected to the positive terminal of the voltmeter. One end of the lead wire is connected to the half-cell and the other end to the negative terminal of the voltmeter. The electrical half-cell potentials are recorded to the nearest 0.01 V. These potential readings give an indication of possible rebar corrosion. **Table 2.1** shows the ASTM interpretation of half-cell potential readings when measured with respect to saturated calomel electrode (SCE) and **Table 2.2** shows the corresponding interpretation with respect to copper sulphate electrode (CSE).

Table 2.1. Interpretations of potential measurements w.r.t SCE

Open Circuit potential (OCP) values	**Corrosion Condition**
< - 426 mV	Severe corrosion, corrosion induced cracking may occur
< - 276 mV	High risk, 90% probability of corrosion
-126 to -275 mV	Intermediate risk, corrosion activity is ascertain
0 to -125 mV	Low risk, 10% probability of corrosion

Table 2.2. Interpretations of potential measurements w.r.t CSE

Potential (E_{corr} vs CSE)	**Probability of Corrosion**
E_{corr} > - 200	Less than 10 %
- 200 > E_{corr} > -350	Unknown
E_{corr} < - 350	Greater than 90 %

The various applications of Half Cell Potential methods are:-

- Assessment of the durability of reinforced concrete members where reinforcement corrosion is suspected.
- Finding high reinforcement corrosion risk areas.
- It can also be used for investigating concrete contaminated with salts.

2.4.2 Linear Polarization Resistance (LPR)

Linear Polarization Resistance monitoring is an effective electrochemical method of measuring corrosion. Monitoring the relationship between potential and current generated between electrically charged electrodes in a process stream allows the calculation of the corrosion rate. LPR is most effective in aqueous solutions, and has proven to be a rapid response technique. This measurement of the actual corrosion rate allows almost instant feedback to operators. LPR monitoring has seen wide industry use for nearly 50 years.

Linear Polarization Theory

Electrical conductivity (the reciprocal of resistance) of a fluid can be related to its corrosiveness. A two or three electrode probe is inserted into the process system, with the electrodes being electrically isolated from each other and the process line. **Fig. 2.10** shows a typical LPR Probe installed in concrete structure.

A small potential in the range of 20mV (which does not affect the natural corrosion process), is applied between the elements and the resulting current is measured. The polarization resistance is the ratio of the applied potential and the resulting current level. The measured resistance is inversely related to the corrosion rate.

The electrical resistance of any conductor is given by:-

$$R=\frac{V}{I} \tag{2.10}$$

Where R = Effective instantaneous resistance

V = Applied voltage

I = Instantaneous current between electrodes

If the electrodes are corroding at a high rate with the metal ions passing easily into solution, a small potential applied between the electrodes will produce a high current, and therefore a low polarization resistance. This corresponds to a high corrosion rate. **Table 2.3** Shows the interpretation of corrosion current density at different corrosion level.

Table 2.3. Interpretation of corrosion level w.r.t. corrosion current density

I_{corr} ($\mu A/cm^2$)	V_{corr} (mm/year)	Corrosion level
≤ 0.1	< 0.001	Negligible
0.1 - 0.5	0.001-0.005	Low
0.5 – 1	0.005-0.010	Moderate
> 1	> 0.010	High

Fig. 2.10 A LPR probe installed in a concrete structure.

There is a direct relationship between the measured corrosion current and the mass of steel consumed by Faraday's Law. Corrosion current can be derived indirectly through half-cell potential measurement through the following expression given by *Stern-Geary*: -

$$I_{\text{corr}} = \frac{B}{\text{Rp}} \qquad (2.11)$$

Where I_{corr} is the change in current (μA /cm^2),

B is a constant relating to the electrochemical characteristics of steel in concrete,

Rp is the polarization resistance expressed as $R_{\text{p}} = \frac{\text{Change in Potential}}{\text{Applied Current}}$

It deserves emphasis that this linear relationship is only valid when the potential change is kept less than 20mV. LPR measurement is very useful in finding the true condition of corrosion in a structure although it is slow compared with the half-cell potential test.

The major advantages to LPR monitoring are**:**

- The speed with which it can provide a measurement of the corrosion rate. Changes in the corrosion rate can typically be detected in minutes, providing an almost instantaneous measuring system. This fast response allows an operator to evaluate process changes, and
- It is particularly useful in monitoring the effectiveness of a prevention program. For example, quick feedback means that inhibitor selection and quantities can be evaluated and fine-tuned in minimal time.
- Another key advantage of LPR monitoring is that it can provide a qualitative pitting tendency measurement, such as whether the tendency for pitting will be shallow and infrequent, or deep and abundant.
- LPR monitoring can also give an indication of metal behaviour, for example when an alloy changes from a passive to an active state, thereby resulting in increased susceptibility to corrosion.
- Caproco LPR probes can often have long lives, depending on the monitoring conditions and maintenance care.
- For projecting probes, the electrodes are replaceable, which extends probe life and offers options in electrode material types for different monitoring objectives.

2.5 CONCLUDING REMARK

In this chapter, corrosion mechanism and different types of corrosion are discussed and the need of various NDT methods for corrosion monitoring of RC structures are reviewed and it is observed that each method possess certain advantages and limitations. It is observed that non-destructive techniques can be used effectively for investigation and evaluating the actual condition of the structures but the choice of a particular NDT method depends upon the property of concrete to be observed such as strength, corrosion, crack monitoring etc. In the present study half cell potential, LPR measurements are taken in order to study the effect of corrosion on steel strand.

CHAPTER 3

CATHODIC PROTECTION

3.1 GENERAL

Cathodic Protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode.

The first reported practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820s *(Bushman. J.B).* The most rapid development of cathodic-protection was made in the United States of America and by 1945, the method was well established to meet the requirements of the rapidly expanding oil and natural gas industry, which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission. The increasing use of cathodic protection in modern times has arisen, in part. The method is now well established and is used on a wide variety of immersed and buried facilities and infrastructure, as well as reinforced concrete structures, to provide corrosion control.

3.2 PRINCIPLES OF CATHODIC PROTECTION

The principle of cathodic protection is in connecting an external anode to the metal to be protected and the passing of an electrical D.C current so that all areas of the metal surface become cathodic and therefore do not corrode. The external anode may be a galvanic anode, where the current is a result of the potential difference between the two metals, or it may be an impressed current anode, where the current is impressed from an external D.C power source. In electro-chemical terms, the electrical potential between the metal and the electrolyte solution with which it is in contact is made more negative, by the supply of negative charged electrons, to a value at which the corroding (anodic) reactions are stifled and only cathodic reactions can take place. The current density and the potential are quite high and after applying Impressed Current Cathodic Protection (ICCP) the potential decrease with decreasing the current density as shown in **Fig 3.1**.

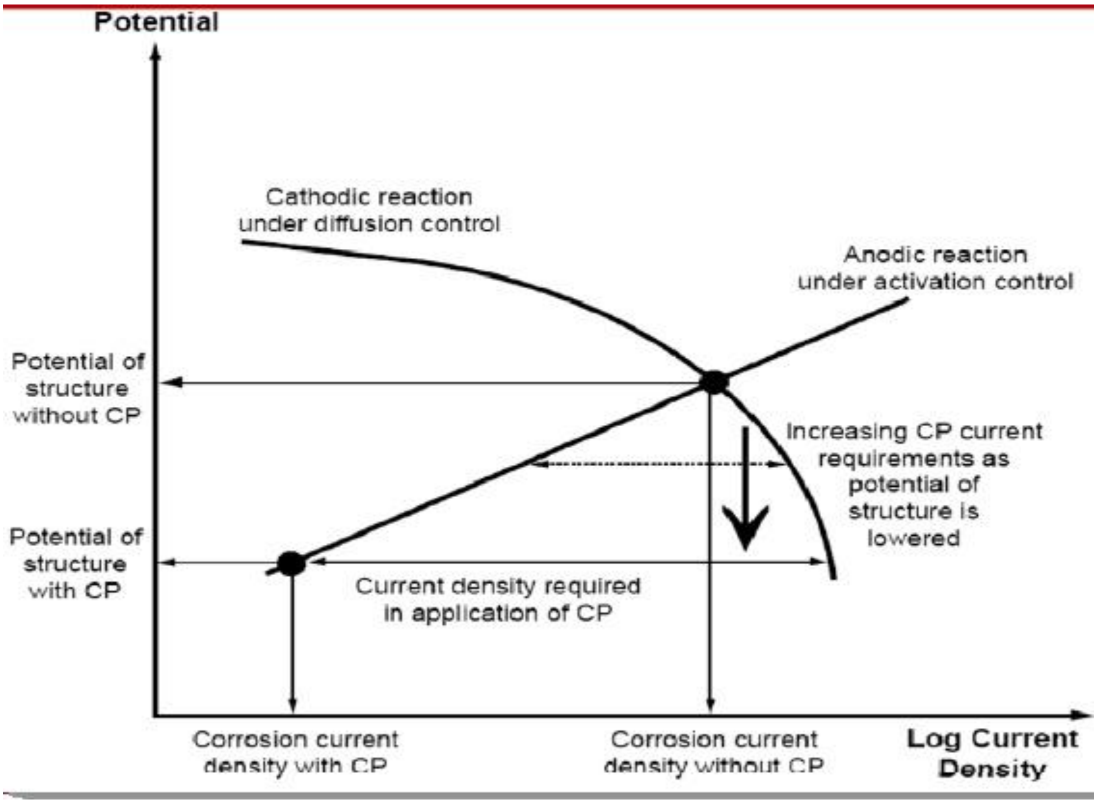


Fig. 3.1 Principles of Cathodic Protection (Ahdash 2010)

3.3 TYPES OF CATHODIC PROTECTION SYSTEMS

There are two main types of Cathodic Protection Systems, they are Impressed Current and Sacrificial Anode. Both type of Cathodic Protection have anode, a continuous electrolyte from the anode to the protected structure, and an external metallic connection (wire). These items are essential for all Cathodic Protection Systems. Two main types of Cathodic Protection Systems are:-

- **By Galvanic (Sacrificial) Anode**

Galvanic anode systems employ reactive metals as auxiliary anodes that are directly electrically connected to the steel to be protected. The difference in natural potentials between the anode and the steel, as indicated by their relative positions in the electro-chemical series, causes a positive current to flow in the electrolyte, from the anode to the steel. Thus, the whole surface of the steel becomes more negatively charged and becomes the cathode. **Fig 3.2** shows the typical view of Sacrificial Anode System. The metals commonly used as sacrificial anodes are aluminium, zinc and magnesium. These metals are alloyed to improve the long-term performance and dissolution characteristics.

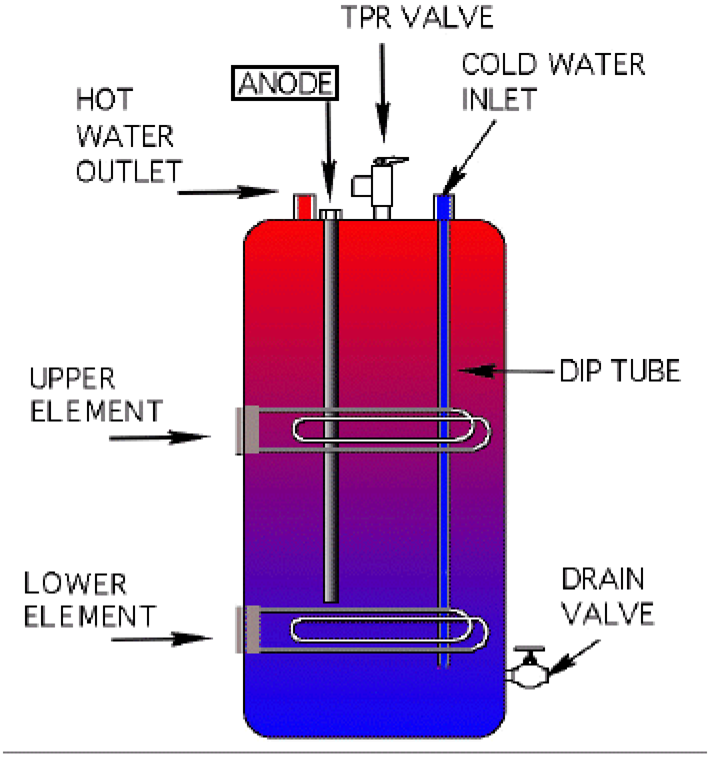


Fig. 3.2 Sacrificial Anode System

- **By Impressed current**

Impressed-current systems employ inert (zero or low dissolution) anodes and use an external source of dc power (rectified A.C) to impress a current from an external anode onto the cathode surface. **Fig 3.3** shows typical view of Impressed Current System. The connections are similar for the application of cathodic protection to metallic storage tanks, jetties, offshore structures and reinforced concrete structures.

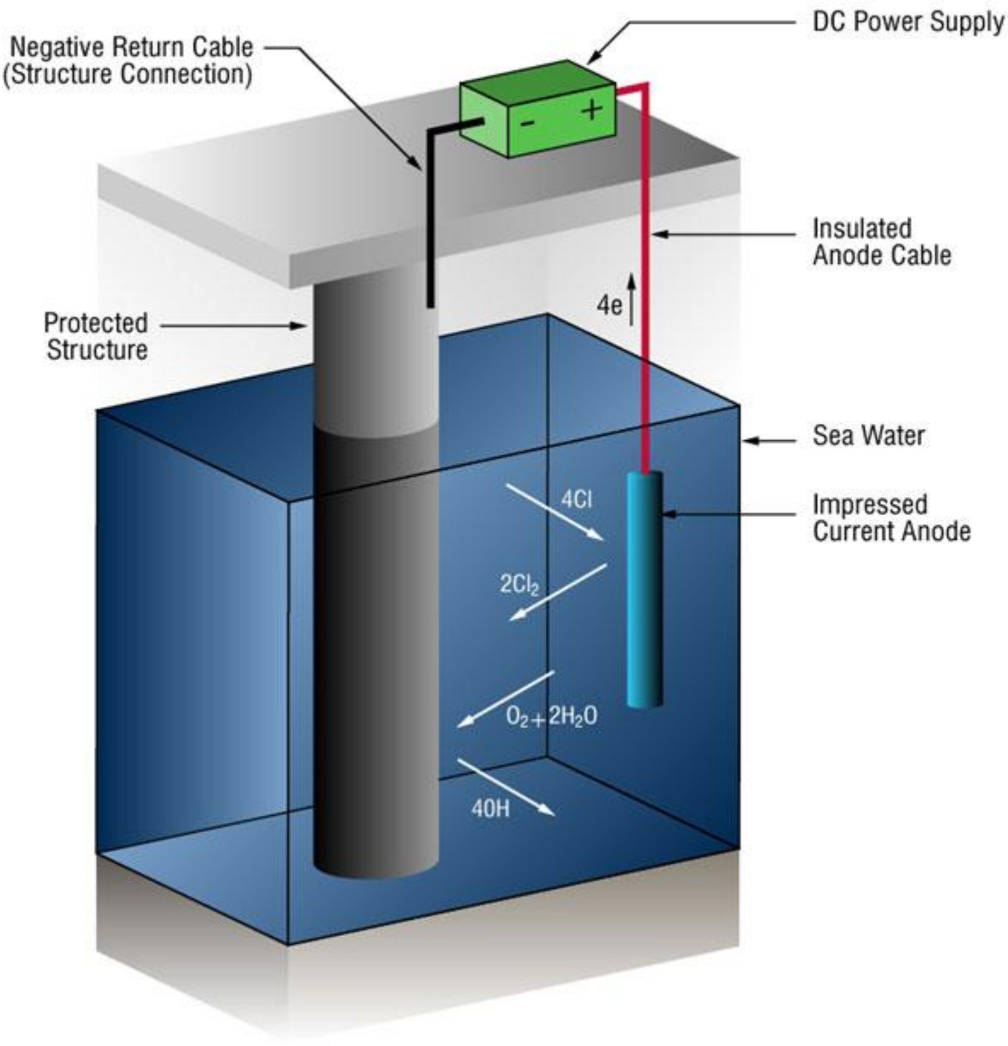


Fig 3.3 Impressed Current System

The comparison between Sacrificial Anode system and Impressed Current system is presented in the following section:-

At the design stage of a cathodic protection scheme, a decision must be made as to whether the scheme will be a galvanic or impressed-current system. In specific circumstances, the use of both types of systems may be appropriate, but care is required to avoid interaction between them. **Table 3.1** shows comparison between sacrificial Anode System and Impressed Current System.

Galvanic systems have the advantage of being:

- Simple to install
- Independent of a source of external electric power

- Suitable for localized protection
- Less liable to cause interaction on neighbouring structures.

Impressed-current installations have the advantage of being:

- able to supply a relatively large current
- able to provide of high DC driving voltages (up to 50V) which enables it to be used in most types of electrolytes.
- able to provide a flexible output that may accommodate changes in, and additions to, the structure being protected.

Table 3.1. Comparison between sacrificial Anode System and Impressed Current System

Sacrificial Anode System	**Impressed Current System**
It requires no External Source	External Power is essential
It can be easily installed and maintained	More complicated system for installation
It can be used in areas where the soil resistivity is low	Limited to use below a soil resistivity of 3000 ohms-cm
It is economical	Less economical for Small Structures
For Small Structures	For Big Structures

3.4 ADVANTAGES AND USES OF CATHODIC PROTECTION

- The main advantage of cathodic protection over other forms of anti-corrosion treatment is that it is applied simply by maintaining a dc circuit and its effectiveness may be monitored continuously.
- Cathodic protection is commonly applied to a coated structure to provide corrosion control to areas where the coating may be damaged. It may be applied to existing structures to prolong their life.
- Specifying the use of cathodic protection initially will avoid the need to provide a “corrosion allowance” to thin sections of structures that may be costly to fabricate. It may be used to afford security where even a small leak cannot be tolerated for reasons of safety or environment. .
- Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte (including concrete). In practice, its main use is

to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion on metals. However, it can be used to protect atmospherically exposed and buried reinforced concrete from corrosion, as the concrete itself contains sufficient moisture to act as the electrolyte.

- Cathodic protection is applied to control the corrosion of steel embedded in reinforced concrete structures (bridges, buildings, port and harbour structures, etc.)
- Cathodic protection can be applied to copper-based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminium alloys, where cathodic potentials have to be very carefully controlled.

Structures that are commonly protected by cathodic protection are the exterior surfaces of:

- Pipelines
- Ships' hulls
- Storage tank bases
- Jetties and harbour structures
- Steel sheet, tubular and foundation pilings
- Offshore platforms, floating and subsea structures

Cathodic protection is used to protect the internal surfaces of:

- Large diameter pipelines
- Ship's tanks (product and ballast)
- Storage tanks (oil and water)

3.5 LIMITATIONS OF CATHODIC PROTECTION METHOD

There are certain limitations to the use of cathodic protection.

- Excessive negative potentials can cause accelerated corrosion of lead and aluminium structures because of the alkaline environments created at the cathode.
- The alkaline conditions generated may also be detrimental to certain coating systems, and may cause loss of adhesion of the coating.

- Hydrogen evolution at the cathode surface may, on high-strength steels, result in hydrogen embrittlement of the steel, with subsequent loss of strength. On some high strength steels, this may lead to catastrophic failures.
- It may also cause disbondment of coatings; the coating would then act as an insulating shield to the cathodic-protection currents.
- Consideration must also be given to spark hazards created by the introduction of electric currents into a structure situated in a hazardous area.

3.6 CONCLUDING REMARKS

The following chapter concludes need of Cathodic Protection and Sacrificial method required, but care must be required to avoid interaction between them, also illustrates the use of Cathodic Protection and its principles involved along with certain advantages and disadvantages involved in using both the methods of protection from corrosion.

CHAPTER 4

FRP IN STRUCTURAL REHABILITATION

4.1 INTRODUCTION

Fibre Reinforced Polymer (FRP), originally developed for the aerospace industry, show immense potential as a material that can be used in civil infrastructure. FRPs are being considered for application to the repair of buildings due to their low weight, ease of handling and rapid implementation.

Recent developments in the field of FRP have resulted in the development of highly efficient construction materials. They have been successfully used in a variety of industries such as aerospace, automobile and shipbuilding. The FRPs are unaffected by electrochemical and electro-mechanical deterioration and can resist corrosive effects of acids, alkalis, salts and similar aggregates under a wide range of temperatures. FRP thus hold a very distinct advantage over steel plates as an external reinforcing device. Moreover, FRP are available in the form of laminas and different thickness and orientation can be given to different layers to tailor its strength according to specific requirements.

Joint Strengthening **Flexural Strengthening**

Fig.4.1 FRP applications to rehabilitate structures

FRP have found their way as strengthening materials of RC elements (such as beams, slabs, columns etc.) in thousands of applications worldwide, where conventional strengthening techniques may be problematic. For instance, one of the popular techniques for upgrading RC elements has traditionally involved the use of steel plates epoxy bonded to the external surfaces (e.g. tension zones) of beams and slabs. This technique is simple and effective as far as both cost and mechanical performance is concerned, but suffers from several disadvantages *(McDonald and Calder, 1982)* such as corrosion of the steel plates resulting in bond deterioration; difficulty in manipulating heavy steel plates in tight construction sites; need for scaffolding; and limitation in available plate lengths which are required in case of flexural strengthening of long girders, resulting in the need for joints. Replacing the steel plates with FRP strips **(Fig 4.1)** provides satisfactory solutions to the problems described above.

It can be concluded here that recent developments in the field of FRPs have resulted in a highly efficient construction material. FRPs are being used increasingly to rehabilitate corrosion affected structures. FRP plates can compensate the loss of longitudinal reinforcement in beams, slabs and columns. FRP sheets are wrapped around beams and columns to rehabilitate them from the loss of shear capacity and confinement due to corrosion of links or stirrups. The efficiency of FRPs in enhancement of bending *(Mukherjee and Joshi 2005; Mukherjee et al. 2007*) and shear *(Mukherjee et al. 2004)* capacities of flexure elements and enhancement of confinement of concrete in compression elements has been well established.

4.2 RETROFITTING NEED IN R.C STRUCTURES

Retrofitting of concrete structures has become an increasingly dominant use of the material in structural engineering applications. Such uses include increasing the load capacity of existing structures (such as existing parking/ garages) that were designed to tolerate far lower service loads, repair of damaged concrete structures etc. **Fig 4.2** shows typical view of FRP Wrapped around Corroded part in Bridge. Repair and rehabilitation work for concrete structures can broadly be classified into two categories:-

- repair for which damage due to deterioration and cracking is corrected to restore the original structural shape, and
- repair which is necessary to strengthen the structural capacity of members whose load carrying capacity is either inadequate or whose strength has been severely impaired due to sustained damage.

Degradation of steel reinforcements due to corrosion (**Fig 4.3**) cracking of concrete due to weathering, rapidly changing traffic needs (both in terms of intensity and load levels) and recent earthquake damages have necessitated the use of strengthening of basic structural components such as slabs, panels, walls, beams and columns. Various researchers have reported that retrofitting by FRP wraps slows down the rate of corrosion thereby preventing the structure from damage *(Kutarba and Hamilton (2007), Spainhour et al. (2008), Bonacci and Maalej (2000)).*

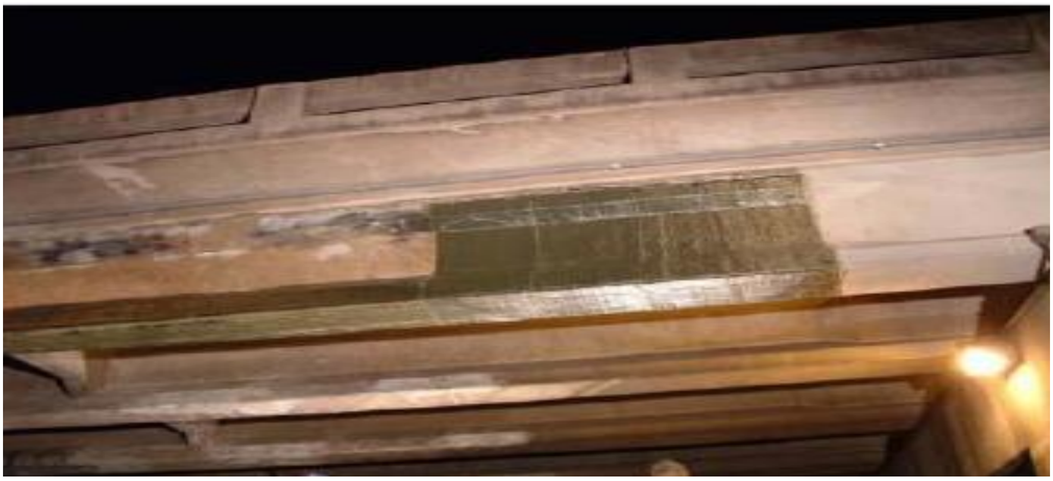


Fig. 4.2 FRP Wrapped around Corroded part in Bridge

Fig. 4.3 Corrosion Damage to a concrete beam

4.3 FRPS AND ITS TYPES

Fibre Reinforced Polymer (FRP) is a relatively new class of composite material manufactured from fibres and resins and has proven efficient and economical for the development and repair of new and deteriorating structures in civil engineering. The mechanical properties of FRPs make them ideal for widespread applications in construction worldwide. FRPs are typically organized in a laminate structure, such that each lamina (or flat layer) contains an arrangement of unidirectional fibres or woven fibre fabrics embedded within a thin layer of light polymer matrix material. The fibres, typically composed of carbon or glass, provide the strength and stiffness. The matrix, commonly made of polyester, Epoxy or Nylon, binds and protects the fibres from damage, and transfers the stresses between fibres. Fibres can be formed from a wide range of amorphous and crystalline materials but in the construction industry the three fibres which are generally used in structural systems are *(Hollaway and Head, 2001).*

- The glass fibre (the E-glass fibre, the S-glass fibre and the Z-glass fibre).
- The aramid fibre (the aromatic polyamides, Kevlar 49 fibre) ,and
- The carbon fibre (the ultra high-modulus fibre, the high-modulus fibre and the high-strength fibre).

4.3.1 Carbon Fibre Reinforced Polymer

Carbon Fibre Reinforced Polymer Composites, or CFRP Composites for short, is a term used to describe a fibre reinforced composite material that uses carbon fibre as the primary structural component. It should be noted that the "P" in CFRP can also stand for "plastic" instead of Polymer. CFRP Composites are lightweight, strong materials used in the manufacturing of numerous products used in our daily life. **Fig 4.4** shows typical view of CFRP Sheet. In general, CFRP composites use thermosetting resins such as epoxy, polyester, or vinyl ester.

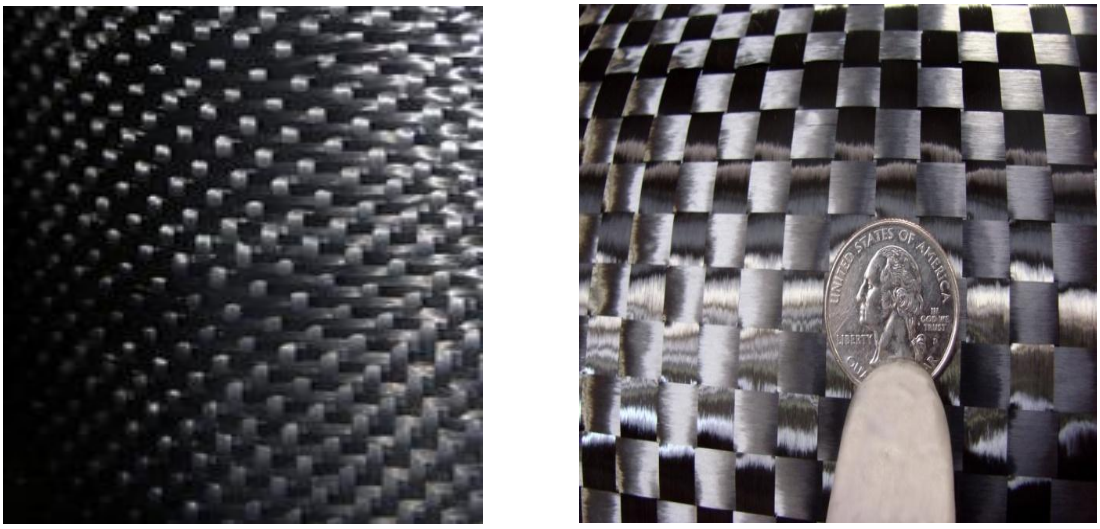


Fig 4.4 Carbon Fibre cloths used in Composites

4.3.2 Glass Fibre Reinforced Polymer

The glass fibres are divided into three classes -- E-glass, S-glass and C-glass. The E-glass is designated for electrical use and the S-glass for high strength. The C-glass is for high corrosion resistance, and it is uncommon for civil engineering application. Of the three fibres, the E-glass is the most common reinforcement material used in civil structures. It is produced from lime-alumina-borosilicate which can be easily obtained from abundance of raw materials like sand. The fibers are drawn into very fine filaments with diameters ranging from 2 to 13 X 10^{-6} m. The glass fibre strength and modulus can degrade with increasing temperature. Although the glass material creeps under a sustained load, it can be designed to perform satisfactorily. The fibre itself is regarded as an isotropic material and has a lower thermal expansion coefficient than that of steel. **Fig 4.5** shows typical view of GFRP Sheet

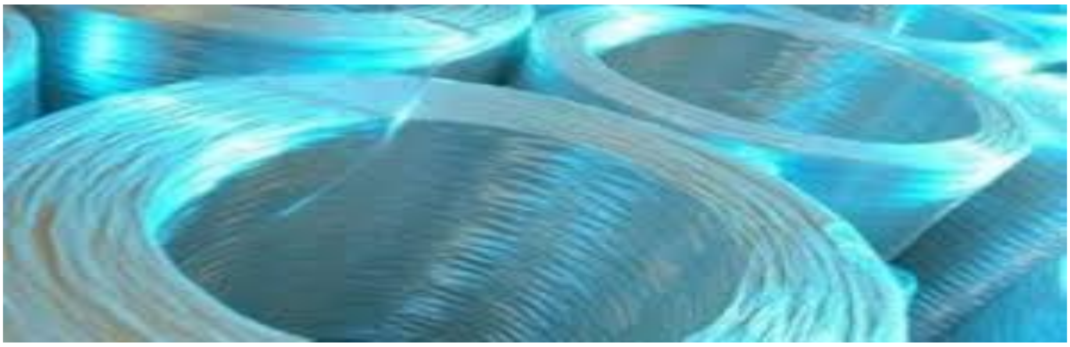


Fig 4.5 Glass Fibre Sheet

4.3.3 Aramid Fibres

These are synthetic organic fibres consisting of aromatic polyamides. The aramid fibres have excellent fatigue and creep resistance. Although there are several commercial grades of aramid fibres available, the two most common ones used in structural applications are Kevlar® * 29 and Kevlar® 49.As an anisotropic material, it's transverse and shear modulus are an order of magnitude less than those in the longitudinal direction. The fibres can have difficulty achieving a chemical or mechanical bond with the resin. **Fig 4.6** shows typical View of Aramid Sheet

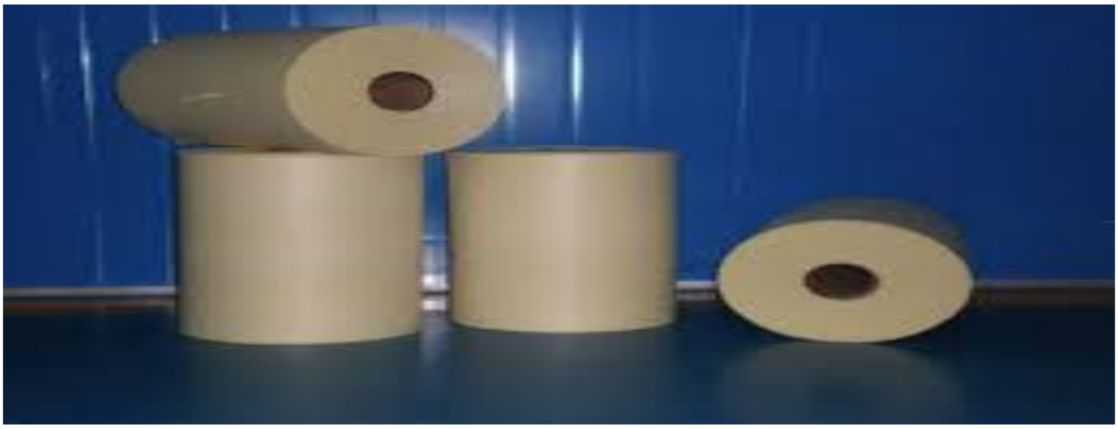


Fig 4.6 Aramid Sheet

4.4 SUITABILITY OF FRP FOR USES IN STRUCTURAL ENGINEERING

The strength properties of FRPs collectively make up one of the primary reasons for which civil engineers select them in the design of structures. A material's strength is governed by its ability to sustain a load without excessive deformation or failure. When an FRP specimen is tested in axial tension, the applied force per unit cross-sectional area (stress) is proportional to the ratio of change in a specimen's length to its original length (strain). When the applied load is removed, FRP returns to its original shape or length. In other words, FRP responds linear-elastically to axial stress.

The response of FRP to axial compression is reliant on the relative proportion in volume of fibres, the properties of the fibre and resin, and the interface bond strength. FRP composite compression failure occurs when the fibres exhibit extreme (often sudden and dramatic) lateral or sides-way deflection called fibre buckling. FRP's response to transverse tensile stress is very much dependent on the properties of the fibre and matrix, the interaction between the fibre and matrix, and the strength of the fibre-matrix interface. Generally, however, tensile strength in this direction is very poor.

Shear stress is induced in the plane of an area when external loads tend to cause two segments of a body to slide over one another. The shear strength of FRP is difficult to quantify. Generally, failure will occur within the matrix material parallel to the fibers. Among FRP's high strength properties, the most relevant features include excellent durability and corrosion resistance. Furthermore, their high strength-to-weight ratio is of significant benefit; a member composed of FRP can support larger live loads since its dead weight does not contribute significantly to the loads that it must bear. Other features include ease of installation, versatility, anti-seismic behaviour, electromagnetic neutrality, excellent fatigue behaviour, and fire resistance. Some of the applications of FRPs are shown in **Fig. 4.7**

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Fig 4.7 FRP bridge deck shapes designed and field implemented in WV and Ohio by the CFC-WVU (Courtesy: CFC-WVU)

4.5 CONCLUDING REMARKS

It can be concluded that recent developments in the field of FRPs have resulted in its use as a highly efficient construction material. CFRPs are being used increasingly to rehabilitate corrosion affected structures. CFRP wraps provide a barrier layer that impedes further corrosion of steel and prevents the increase in volume of RC members due to rusting by applying confinement pressure, thereby preventing dislodging of concrete cover.

CHAPTER 5
LITERATURE REVIEW

5.1 GENERAL

This chapter represents thorough review of literature on use of FRPs for protection of rebar against corrosion. The FRPs are used both as passive protection measure and as active protection measure against rebar corrosion.

5.2 PASSIVE PROTECTION BY FRP

Sen (2003) presented an overview of the application of fibre-reinforced polymers (FRP) for repairing corrosion-damaged structures by external wrapping. The rationale, design and durability for such repairs were addressed and significant research findings were highlighted. Several field applications were described and new and innovative practices identified. Recommendations were also made to improve future performance. Based on the sample geometry, the literature is reviewed for small scale RC cylindrical and column samples and large scale beam samples in the following sub section.

5.2.1 Small Samples

Debaiky et al. (2002 a) discussed the use of carbon fibre-reinforced polymer CRP wraps as a rehabilitation technique far corroded reinforced concrete columns. Two groups of cylindrical RC specimens were subjected to either an aggressive environment or impressed current (galvanostatic) corrosion. Part of each group was wrapped before the corrosion initiation. The wrapping consisted of one or two layers of CFRP applied either fully or partially over the cylinder height. Condition of the cylinders was monitored through half-cell potential measurements, linear polarization resistance, and crack mapping. At the end of the experiment, the cylinders were tested to failure under axial compression. Concrete was analyzed for total chloride content to study the efficiency of the wraps as a barrier for contaminated water. Steel cages were chemically cleaned to calculate the mass lost due to corrosion. It was concluded that applying CFRP wraps significantly decreases corrosion activity when applied over entire specimen. The application of the wraps before corrosion propagation prevented corrosion from taking place, while the application of the wraps after corrosion occurrence dropped the rate of corrosion sharply. Authors suggested that this effect is probably due to the epoxy saturant used to apply the CFRP sheets rather than the sheets itself.

Debaiky et al. (2002 b) summarized four years of laboratory testing into the use of FRP wraps in repair of twelve circular reinforced concrete columns. Inducing corrosion in the columns using an aggressive environment that simulated natural corrosion was focused. FRP wraps were applied to eight columns as a repair system after achieving a satisfactory degree of corrosion damage. Four columns were treated for chloride contamination before applying the wraps to investigate the need for this process. The columns were subjected to a harsh environment after wrapping to monitor the corrosion activity. The FRP wraps were found to reduce the corrosion in the repaired columns.

Pantazopoulou (2001) presented the results of an experimental parametric study of jacketing of corrosion damaged structures by fibre reinforced composite sheets as a repair alternative for corroded structures. Several small size concrete columns with various reinforcement configurations were subjected to accelerated corrosion conditions in the laboratory. After achieving a target level of steel loss the columns were repaired using a variety of repair alternatives. Jacketing of the damaged specimens was done with glass-fibres wraps, in combination with grouting the voids between the jacket and the original lateral surface of the specimen with either conventional or expansive grouts. To protect the glass fibre material from exposure to alkali activity of the fresh grout, and to reduce the supply of oxygen and water to the mechanism of corrosion, different types of diffusion barriers were considered in the study. The efficacy of each repair system was evaluated by assessing the post-repair corrosion resistance of the specimens under repeated exposure to accelerated conditions; and the mechanical strength and ductility enhancement under concentric compression loading.

Green et al. (2002) has proved that fibre reinforced polymer (FRP) for wrapping reinforced concrete columns as a very promising repair technique for deteriorating structures. Effect of the wraps on the corrosion of steel in concrete was investigated. Results obtained indicated that the CFRP wraps applied over corrosion-damaged reinforced concrete columns will decrease the corrosion rate of the reinforcement and restore the structural integrity of the column.

Spainhour et al. (2008) investigated the corrosion performance of steel reinforcement embedded in concrete encased by carbon fibre reinforced polymer (CFRP) wraps with two different types of epoxies namely-West System 105 (WS), a marine grade epoxy designed specifically for reinforcing fabrics and, Sikagard 62 (SG), a thick, gray epoxy designed for use as a thick, corrosion-resistant, moisture-insensitive protective coating. Nine cylindrical test specimens were cast with different number of CFRP layers with different epoxies. The CFRP wraps were applied to samples in a hand lay-up procedure. An initial coat of epoxy was applied to the bottom and sides of the samples, followed by the application of successive wetted fabric layers then followed by a final clear coat of epoxy. The specimens were immersed, in a 5% Nacl solution at a room temperature and connected to a 12-volt DC power supply, thus impressing a current such that the reinforcing bars are anodic. These experimental results showed that WS epoxy coating has no effect on the onset or rate of corrosion but WS epoxy coating with CFRP wraps delay the onset of corrosion of WS samples takes over twice as long when samples are wrapped. However in the case of SG samples, an epoxy coating was able to delay the onset of corrosion by a factor of 2, and for wrapped SG samples the onset of corrosion takes 4–8 times longer .These results indicate that the SG epoxy with even a single CFRP layer is enough to inhibit the passage of salt water, protect the concrete from deterioration and considerably slow the overall corrosion rate with lower amounts of corrosion mass loss thereby providing a longer period of protection to the underlying concrete and embedded steel bars.

Wootton et al. (2003) also reported that CFRP wraps effectively reduced the corrosion rate in reinforced concrete cylinders.

5.2.2 Large Samples

Berver et al. (2002) wrapped the corrosion-damaged reinforced concrete structures with composite materials in an attempt to starve them of oxygen, moisture, and chlorides so as to eliminate corrosion. Laboratory and field investigations were carried out on columns and beams that have suffered corrosion damage due to chloride penetration.

Masoud et al. (2005) studied the fatigue performance of corroded RC beams repaired with FRP sheets experimentally and analytically. The FRP sheets were applied after the main reinforcing bars were corroded to an average mass loss of 5.5%. Following FRP repair, some specimens were tested immediately to failure, while the other repaired specimens were subjected to further corrosion before being tested to failure to investigate their post repair (long-term) performance. Reinforcement steel pitting due to corrosion reduced the fatigue life significantly. The FRP wrapping had no significant effect on the fatigue performance, while using CFRP sheets for flexural strengthening enhanced the fatigue performance significantly. The fatigue results were compared to smooth specimen fatigue data to estimate an equivalent fatigue notch factor for the main reinforcing bars of the tested specimens.

Badawi and Soudki (2005) studied the effect of carbon fibre-reinforced polymer (CFRP) confinement on the cracking damage induced by impressed current-accelerated corrosion of reinforced concrete beams. The investigation was carried out for two different corrosion configurations, namely uniform and shear-span corrosion at three different degrees of corrosion. Uniform corrosion along the whole length of the beams and shear-span corrosion at 900 mm from each beam end were considered. The different degrees of corrosion were achieved using an accelerated corrosion technique with an impressed current. It was concluded that CFRP laminate confinement reduces corrosion expansion by up to 70% and slows the rate of corrosion through decreasing the corrosion mass loss by up to 35%. It also reduced the reduced the corrosion mass loss in the post repaired beams by 35 and 33% for the shear-span and uniform corrosion beams, respectively, compared to the unwrapped corroded beams.

Masoud and Soudki (2006) prepared ten large scale beam specimens; one was neither strengthened nor corroded to serve as a reference. Three specimens were corroded and not repaired. The remaining six beams were corroded and repaired with FRP sheets. The FRP sheets were applied after the main reinforcing bars were corroded to a 5.5% mass loss. Some FRP repaired specimens were subjected to further corrosion to investigate their post-repair performance. The corrosion activity was evaluated using non-destructive techniques of half cell potential measurements with reference to Silver/ Silver Chloride electrode as per ASTM C876-91 Standard. The destructive techniques included evaluation of the mass loss of the main reinforcing bars. The experimental results showed that the corrosion potential decreased with the progress of corrosion, and the FRP repair caused a higher rate of decrease in the corrosion potential with time than that observed when FRP was not provided. Half cell potential measurements also indicated that wrapping the specimens with GFRP sheets had the main effect in reducing the corrosion activity, whereas, the CFRP sheets provided for flexural strengthening had no significant effect on the corrosion activity. Results showed that mass loss of the main reinforcing bars due to corrosion was reduced by up to 16% because of FRP repair.

5.3 LITERATURE REVIEW ON ACTIVE PROTECTION BY FRP

Mukherjee et al. (2004) investigates active protection of the steel embedded in concrete that is treated with surface-bonded carbon FRP. The electrically conductive carbon fibre is used as an anode while the reinforcing bar is used as a cathode. Concrete cylinder specimens with embedded steel bars are immersed in salt water and anodic current is passed through the reinforcement to initiate cracking in concrete as a result of accelerated corrosion of steel. Carbon FRP sheets have been bonded adhesively to the cylinders. The adhesive has been modified to impart electrical conductivity. Specimens were exposed to a highly corrosive environment for a specified time. Pullout strength, mass loss, potentiodynamic scans, and the half-cell potential of steel are reported as metrics of performance of the samples. The proposed technique has been very effective in retarding the corrosion of steel.

Nimrat Pal Kaur (2011) illustrated the findings of an experimental investigation carried out on six slab specimens for evaluating the performance of concentrically placed rebar of 25 mm diameter in chloride contaminated concrete at three different stages of corrosion. Corrosion rate were obtained by Electrochemical Techniques (Half Cell Method and Linear Polarization Technique) and by Ultrasonic Technique, by wrapping CFRP Sheets around Corroded Slab Specimens for Active protection, using Impressed Current System. The rebar was protected by supplying two levels of impressed current: 10 mA and 30 mA. The protected slabs were monitored for a period of 40 days and it was observed that the CFRP is able to protect the specimens against rebar corrosion. However, type of protection achieved depends upon the amount of impressed current. It was observed that 10mA of applied current is sufficient to protect the specimens effectively.

Sunil Saharan (2012) extended the work done by *Nimrat Pal Kaur (2011)* in which actively protected specimens were monitored further for six months. The protection provided by the impressed current stabilized during the duration of six months.

Gadve (2008) investigates active protection of the steel embedded in concrete cylinders, treated with surface bonded carbon FRP. The electrically conductive carbon fibre is used as anode while the reinforcing bar is used as cathode in the present active protection. Anodic current was passed through the reinforcement in both specimens to initiate cracking in concrete. Carbon FRP sheets have been adhesively bonded to the cylinders. The adhesive has been modified to impart electrical conductivity. Specimens were exposed to highly corrosive environment for specified times. Several performance metrics have been reported and the relative efficacies of active and passive protection have been studied. It was established that the active protection technique is very effective in retarding the corrosion of steel. However, an optimum current density must be maintained to avoid damages at the interfaces of steel and concrete.

Jing et al. (2010) studied the behaviour of a new type of secondary anode material made of carbon fibre reinforced cement used for cathodic protection of steel in concrete. The carbon fibres were isotropic polyacrylonitrile (PAN) based, unsized, and of length 5 mm to 10 mm, as obtained from SGL Carbon Co. (SGL, Germany). The mechanical, electrical and electrochemical properties of conductive mortar were Investigated.

In this the cylindrical specimen, 30 mm in diameter and 30 mm in height, used for the study of electrochemical behaviour of the conductive mortar. Specimens containing 0.05%-0.8% by volume of fibres were prepared in a laboratory mortar mixer. The anodic behaviour of the conductive mortar was studied with galvanostatic tests on small cylindrical probes immersed in saturated solutions. In order to improve the anodic polarization a designed current density of 200 mA/m^2 was applied.

Experimental results show that addition of carbon fibre enhances the strength and ductility of the mortar, as well as the electrical property and investigated that conductive mortar can be used in cathodic protection of reinforced concrete. The addition of carbon fibre enhances the mechanical performance of mortar. Electrochemical property of mortar with higher fibre content is more inclined to deteriorate when chloride ions exist. So optimum fibre content in the conductive mortar should be in the range of 0.5 vol% to 0.7 vol%.

Philippe De Schoesitter (2010-2011) studies the Technical feasibility of the usage of carbon fibre reinforced polymer for externally bonded reinforcement of reinforced concrete structures (CFRP EBR) for active cathodic protection (CP) of the reinforcement steel. Through linear polarization, the effectiveness of the ICCP was monitored. The corrosion rate was measured in different ways both during and at the end of the test program. In this small chloride contaminated mortar cylinders of diameter 48mm and height 100mm were prepared. A smooth steel bar was embedded in the concrete axially, over a length of 80mm. The steel was used as the cathode and the CFRP wrap as anode for the induced current CP (ICCP). To initiate and accelerate the corrosion process, chlorides were added to the mortar mixture, and the samples were partially immersed in a NaCl bath during the ICCP program.

Experimental result shows that cathodically protected specimens had substantially lower corrosion rates. The higher the conductivity of the epoxy, the lower the absolute corrosion rates were, and lower the corrosion rate evolution was. Most of open circuit potentials (OCPs) show an upward (less negative) shift, as a result of the decrease of protection current I_{prot}. Whereas the fibreless specimens show downward evolution, indicating safer steel condition despite of I_{prot} drop.

5.4 LITERATURE REVIEW ON ELECTROCHEMICAL TECHNIQUE

Wheat (2002) used polarization resistance techniques to determine corrosion rates of steel in concrete. It was recognized that the rates that are determined reflect relative rates and may be influenced by factors such as localized forms of corrosion as well as varying surface areas of the corroding metal. The use of polarization resistance measurements on steel having a ribbed surface and in a concrete environment that is not homogeneous is certainly a deviation from the Stern–Geary analysis on which the technique is based.

Tamer and Soudki (2003) aimed to study the effect of varying impressed current density level on the actual degree of steel reinforcing bar corrosion as well as on the concrete strain behaviour due to expansive stresses caused by the corrosion products, crack width due to corrosion of reinforced concrete prism specimens, and degree of corrosion or mass loss of steel reinforcing bars in concrete prisms. A summary of some of the previous accelerated corrosion tests on reinforced-concrete members is also presented. The results showed that, accelerated corrosion using the impressed current technique was effective in inducing corrosion into the steel reinforcement in concrete up to 7.27% mass loss. With respect to Faraday's law, the use of different current densities has no effect on the percentage of mass loss. However, increasing the level of current density above 200 mA/cm2 results in a significant increase in the strain response and crack width due to corrosion of the steel reinforcement.

Angst et al. (2009) studied linear polarization method (LPR) and Electrochemical impedance spectroscopy (EIS) for detecting active corrosion and stated that the most accurate technique to detect depassivation of the steel is the measurement of the linear polarization resistance, which is inversely proportional with the corrosion current as described by the Stern–Geary-equation. By applying the Stern–Geary-equation and assuming Tafel slopes the corrosion rate can then be calculated.

Care and Raharinaivo (2007) carried out a study with the objective to check how accelerated corrosion tests simulate steel corrosion in real reinforced concrete structures. Corrosion was accelerated, by polarizing reinforcement against a counter-electrode, with an anodic current. The results showed that, like under natural condition, in accelerated tests, rust formed on steel expands, makes its concrete cover crack, and induces a loss of bonding between reinforcement and concrete. The corrosion products obtained are similar to what is observed under natural condition.

Accelerated corrosion test by impressed current is confirmed to be a valid method to study the corrosion process of steel in concrete, and its effects on the damage of concrete cover. This study shows also that cracks appearance and propagation in concrete can be monitored with non destructive techniques.

Bhattacharjee et al. (2009) illustrated the findings of an experimental investigation carried out on large number of specimens for evaluating the performance of different types of rebar in chloride contaminated concrete made with different types of cement through different corrosion rate techniques. Corrosion rate were obtained by linear polarization resistance (LPR) technique with guard ring arrangement and AC impedance spectroscopy.

Bhavneet et al. (2010) used two non-destructive techniques namely electrochemical LPR measurement and ultrasonic guided waves for determining the corrosion initiation and progression. It was concluded that electrochemical measurements are effective only in monitoring corrosion initiation and are not useful to measure corrosion progression whereas ultrasonic guided waves are effective for both monitoring and progression of corrosion.

Goueygou et al. (2008) experimentally studied the effectiveness of two non-destructive testing techniques: the measurement of electrical resistivity and the transmission of ultrasonic surface waves, to detect the width and depth of crack pattern. Rectangular concrete slabs reinforced with 10 mm bar and 25 mm cover the test specimens were cast. A major crack was induced in the middle of the specimen using a three point bending setup. Electrical resistivity measurements were made with a four probe square device and Ultrasonic Rayleigh wave technique was used to measure pulse velocity, phase velocity and peak attenuation. The test results showed that, both techniques were able to detect the presence of a main crack in the middle of the specimen but the secondary cracks around the main crack and the depth of the crack were detected only by ultrasonic technique.

Broomfield et al. (2002) applied corrosion monitoring techniques to monitor durability in new constructions, and as well as on existing structures to evaluate rehabilitation strategies such as corrosion inhibitor applications and patch repairs.

Corrosion monitoring systems include linear polarization, concrete resistivity and half cell potential measurements. The author concluded that this monitoring system is very effective to access the condition of new and rehabilitated structures well in time.

Li et al. (2006) studied the application of steel thin film electrical resistance (TFER) sensor for in situ corrosion monitoring. For this, the sensing element of the sensor was designed to have a multiple-line pattern, in order to study the sensitivity of TFER to various corrosive environments, and the feasibility to detect the localized feature of corrosion. The polarization resistance (Rp) of thin films and bulk steel were measured by the linear polarization resistance (LPR) method in order to investigate the difference in corrosion behaviour of thin films and bulk steel. The test results showed that the corrosion behaviour of bulk steel could be successfully predicted using the steel thin film electrical resistance (TFER) sensor. Moreover, the TFER sensor with the multiple-line pattern showed the enhanced sensitivity to localized corrosion phenomena. The TFER sensor can also be applied to atmospheric conditions where it is difficult to apply an electrochemical method because of the absence of a proper electrolyte in dry cycles. In summary, the TFER sensor could be a reliable tool for corrosion monitoring in a wide range of industries.

Park et al. (2003) tried to establish the suitability of the type of sensor system to evaluate the corrosion behaviour of rebar. For this, a correlation was developed between sensor output and corrosion rate of reinforcing steel in a concrete environment by using two galvanic sensor systems. Non destructive methods such as open-circuit potential, linear polarization resistance (LPR) measurement and electrochemical impedance spectroscopy (EIS) were used for current measurements and the test results indicated that the steel/copper sensor is a reliable non destructive method of determining actual corrosion rate in a concrete environment. However, steel/stainless steel sensor is not suitable for detecting corrosion damage of reinforcing steel due to the low galvanic current output.

Song et al. (2007) reviewed all the electrochemical and non destructive techniques from the point of view of corrosion assessment and their application to bridges, buildings and other civil engineering structures.

Pradhan et al. (2010) experimentally investigated the various corrosion parameters that specify the possibility and the magnitude of corrosion in concrete through different electrochemical corrosion tests namely potential measurement, corrosion rate measurement and potentiodynamic polarization test. The performance of concrete both in internal chloride and external chloride exposure conditions was studied. From the results it was observed that, dropped half-cell potential value obtained from external chloride exposure mostly lie in the active zone. In addition it was observed that there was significant difference in corrosion current values obtained from both internal and external chloride exposure conditions. Through this work it was confirmed that the critical chloride level leading to corrosion initiation was not a unique value and varies with steel type, cement type, and w/c ratio.

Sathiyanarayanan et al. (2006) studied the performance of galvanostatic pulse technique for monitoring the corrosion of steel in concrete. Corrosion rate values obtained by weight loss method and LPR techniques were compared with the values obtained from galvanostatic pulse technique for steel reinforced in M15, M20, M30 and M35 grade concrete containing 0-5% Nacl. Concrete cubes reinforced with 5 mm steel rod exposing a length of 50 mm were cast. The conventional three electrode assembly consisting of stainless steel (counter electrode), saturated calomel (reference electrode) and reinforcing steel (working electrode), was used for both LPR and galvanostatic pulse measurements. The corrosion rate from mass loss was calculated by using the following relationship

$$\text{Corrosion rate (mmpy)} = \frac{87.6 \times \text{mass loss (mg)}}{\text{Area (cm}^2\text{)} \times \text{Time (h)} \times \text{Density}} \qquad (5.1)$$

The test results indicated that the corrosion rate values of steel in concrete are dependent on the strength as well as the percentage of chloride present in the concrete. On increasing the strength from M15 to M35, the corrosion rates decreased for a given chloride concentrations. Further it was found that the corrosion rates obtained by the galvanostatic pulse method and weight loss method agree well in most of the studied system. However, the corrosion rate values obtained by the LPR method were found to be one order lower than that of the actual corrosion rates for steel in concrete in the presence of chloride due to the inclusion of resistance of the concrete in the measured Rp values. Therefore galvanostatic pulse technique were found to give more reliable results about the state of reinforcing steel in concrete and the rate of corrosion.

Sakr (2005) carried out an experimental study to investigate the effect of different percentage (from 2% to 10%) of tricalcium-aluminate (C_3A) in cement on corrosion of reinforcing steel bars when subjected to chloride and/or sulphate media using different electrochemical techniques namely; half-cell potential measurement, impressed voltage method and impressed current method. The corrosion rate was calculated using Faraday's law. It was observed that increasing the percent of C3A from 2% to 10% decreases the corrosion of reinforcing steel immersed in 5% NaCl solution and optimum percentage of C3A to control corrosion of reinforcing steel in both chloride and sulphate containing media is 6%. The test results showed that each electrochemical technique provided some but not all information about the corrosion resistance of steel bars embedded in cement in exposed to aggressive media.

So et al. (2008) investigated galvanostatic pulse transient technique to evaluate the corrosion of steel in concrete and compared it with conventional LPR method. Galvanostatic pulse transient measurements were conducted on a number of short sections of steel bar embedded in concrete. Stern-Geary equation was used for LPR measurements. The electrochemical potential transient response was analyzed to obtain separate equivalent electronic components, comprising a series of resistances and capacitances, whose values are dependent on the corrosion condition of the reinforcing steel. The corrosion rate was evaluated from a summation of the separate resistive components and compared with corrosion rate determined from taking a conventional LPR on the same specimens. The results obtained showed that the galvanostatic pulse transient technique enables the separate components of the polarization resistance to be resolved, which offers significant advantages over the LPR method and provides a more conservative evaluation of the ongoing rate of corrosion.

Koleva et al. (2006) tested small scale cylindrical RC specimen to investigate the corrosion behaviour of steel in concrete. Steady direct current was applied to reinforcement steel (cathode) for corrosion prevention and protection. A cylindrical titanium mesh served as counter electrode and saturated calomel electrode (SCE) as reference electrode. The specimens were monitored using LPR and EIS techniques. Tafel plots were used to find the electrochemical parameters such as polarization resistance (Rp), corrosion potential (Ecorr) and corrosion current density (Icorr). The corrosion current density was estimated by Stern–Geary equation. Test results indicated that the corrosion current density decreased significantly for protected specimens.

5.5 CONCLUDING REMARKS

Following chapter presents literature review on electrochemical techniques and protection of R.C structures using FRPs sheets, and found that FRP sheets can be used both as passive protection and active protection measure. Also, a number of techniques are available to monitor rebar corrosion. However, electrochemical techniques are most suitable and efficient in monitoring corrosion of rebars.

CHAPTER 6

EXPERIMENTAL PROGRAMME

6.1 GENERAL

Following chapter represents experimental setup to evaluate the effectiveness of using FRPs for Active Protection of R.C Structures. The effectiveness is monitored by the Electrochemical techniques namely Half cell Potential and LPR measurements.

6.2 EXPERIMENTAL PROCEDURE

The objective of this present investigation is to explore the efficacy on FRP used in structural repairs that are damaged by corrosion. Since the structure is repaired after it has been damaged by corrosion, therefore experimental program necessitates creation of conditions where corrosion has already set in prior to FRP intervention. Corrosion is a process that requires several years and decades to set in. Preparation of samples that emulate the field conditions would be a long procedure. Their performance needs to be monitored over several years. Therefore, it is prudent to devise a pilot test that introduces rapid corrosion and provides quick results to enable us to identify the promising areas of further long-term investigations. In the present work the rapid corrosion is done by impressed current technique.

The detailed experimental procedure involves the following steps:-

- Findings of basic properties of materials namely cement, fine aggregates, coarse aggregates and steel tendons as per relevant Indian standard specifications.
- Taking tendon of diameter 12.7 mm and cutting the tendons to required length 600 mm and cleaning it with Hexane Reagent solution.
- Then Coating the length of 150 mm of the pre-stressing tendons from both ends with epoxy paint so as to protect that portion of tendon from corrosion, no current will pass through that portion due to epoxy coating.
- Preparation of nine block specimens of size 300 x 300 x 60 mm using M30 grade of concrete with pre-stressing tendons placed.
- Further subjecting the block specimens to accelerated corrosion by impressed current technique, supplying initial voltage of 5 mV.

- Retrofitting of corroded slab specimens is done and further Active Protection of strand is done by supplying applied current of 10mA. Protection is provided at 3 different stages namely:-
    - During corrosion initiation.
    - At the time of onset of crack.
    - 2 days after the onset of crack.

All these steps are explained in systematic manner in the following sections:-

6.3 MATERIAL SYSTEM

The basic materials used in the preparation of specimens are cement, coarse aggregates, fine aggregates, water, pre-stressing tendons. The properties of these basic materials are as under:-

6.3.1 Cement

Portland Pozzolana cement (PPC) is used for the present investigation. The cement is of uniform colour i.e. grey with a light greenish shade and is free from any hard lumps. Summary of the various tests conducted on cement are given in **Table 6.1** All the tests are carried out in accordance with procedure laid down in IS: 8112-1989.**Table 6.2** shows the compressive strength of cubes at 7 and 28 days after curing.

Table 6.1. Physical Properties of cement

S.NO.	Characteristics	Obtained result	Standard values
1.	Normal Consistency	28%	-
2.	Initial setting time	70min.	Should not be less than 30 min.
3.	Final setting time	300 min.	Should not be more than 600 min.
4.	Fineness	6 %	< 10
5.	Specific Gravity	3.148	-

Table 6.2. Compressive Strength of cement- (Cement : Sand= 1:3)

S.No.	Days of Curing	Compressive Strength (MPa)
1.	7 days	27
2.	28 days	39.3

6.3.2 Fine Aggregates

The fine aggregates used for the experimental work is locally procured and conformed to grading zone III. Sieve Analysis of the fine aggregate is carried out in the laboratory as per IS 383-1870. The sand is first sieved through 4.75mm sieve to remove any particle greater than 4.75 mm sieve and then washed to remove the dust. The physical properties and sieve analysis of fine aggregates are shown in **Table 6.3** and **Table 6.4** respectively.

6.3.3 Coarse Aggregate

Crushed stone aggregate of size 20 mm and 10mm are used as coarse aggregate throughout the experimental study. The aggregates are washed to remove dust and dirt and are dried to surface dry condition. The aggregates are tested as per IS: 383-1970. The results of various tests conducted on coarse Aggregates are enlisted in **Table 6.5, table 6.6** and **table 6.7.**

6.3.4 Water

Fresh and clean tap water is used for casting the specimens in the present study. The water is relatively free from organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard.

6.3.5 Prestressing Tendons

A standard size of tendons of length 600 mm length and 12.7 mm nominal diameter were used .**Table 6.8.** shows the properties of 12.7 mm diameter strand as provided by the company. The tendons are cleaned with sand paper using hexane reagent solution and then finally cleaned with petrol to remove unwanted particles from the surface of tendons. The white shining surface was maintained in the laboratory until it was embedded in concrete. **Fig 6.1** shows cleaned tendons using Hexane reagent solution.

Fig 6.1 cleaned Tendons using Hexane reagent solution

Table 6.3. Physical properties of Fine Aggregate

S.No.	Characteristic	Value
1.	Specific gravity	2.567
2.	Fineness modulus	2.465
3.	Water absorption	1.914 %
4.	Grading zone	Zone III
5.	Bulk Density	Loose-1.48 g/cc Compacted-1.6 g/cc

Table 6.4. Sieve analysis of Fine Aggregate

S.No.	Sieve size	Mass retained (gm)	Percentage passing (%)
1.	10 mm	0	100
2.	4.75 mm	12.5	98.75
3.	2.36 mm	49	95.1
4.	1.18 mm	163.5	83.65
5.	600 µ	107.5	89.25
6.	300 µ	289.5	71.05
7.	150 µ	306	69.4
8.	PAN	59	94.1
Total Weight taken = 1000 gm Fineness Modulus of Fine Aggregate = 2.465			

Table 6.5. Physical properties of Coarse Aggregate of 20 mm and 10 mm diameter

S.No.	Characteristics	Values of 20 mm	Values of 10 mm
1	Type	Crushed	crushed
2	Specific Gravity	2.66	2.63
3	Total Water Absorption	0.64 %	0.56 %
4	Fineness Modulus	8.625	6.833

Table 6.6. Sieve Analysis of Coarse Aggregate (20 mm size)

S.No.	Sieve Size	Mass Retained (Kg)	Percentage Retained	Cumulative Percentage Retained	Percentage Passing
1.	20 mm	0.13	3.68	3.68	96.32
2.	10 mm	3.28	92.91	96.59	3.41
3.	4.75 mm	0.1	2.83	99.42	0.58
4.	PAN	0.02	0.56	∑=199.69	
Total Mass taken = 3.53 Kg Fineness Modulus of coarse aggregate (20 mm)= $\frac{(199.69+500)}{100} = 6.99$					

Table 6.7.Sieve Analysis of Coarse Aggregate (10 mm)

S.No.	Sieve Size	Mass Retained (Kg)	Percentage Retained	Cumulative Percentage Retained	Percentage Passing
1.	20 mm	0	0	0	100
2.	10 mm	0.7	49.64	49.64	50.36
3.	4.75 mm	0.61	43.26	92.9	7.1
4.	PAN	0.1	7.09	∑=142.54	
Total Mass taken = 1.41 Kg Fineness Modulus of coarse aggregate = $\frac{(142.54+500)}{100} =6.42$					

Table 6.8. Properties of Strand of 12.7 mm Diameter

S.No.	Properties of Strand	Value
1.	Nominal Diameter (mm)	12.7
2.	Nominal Steel area (mm^2)	100.1
3.	Nominal Mass (Kg/m)	0.786
4.	Minimum Breaking Load (KN)	184
5.	Minimum Proof Load (0.2 % Proof Stress)	156.4
6.	Minimum Elongation to Fracture in 600 mm (%)	3.5
7.	Relaxation after 1000 hours at 0.8 % Breaking Load (%)	2.5
8.	Modulus of Elasticity (MPa)	180-205

6.3.6 CFRP Materials

CFRP wraps used for the study are commercially available world over. Carbon FRP sheets has been used in present investigation. **Fig 6.2** shows the Unidirectional CFRP sheets of cross section (300 x 0.1176) mm, used for wrapping and protecting the corroded samples. The CFRP sheets are obtained from BASF construction chemicals and building systems. **Table 6.9** shows the properties of CFRP Sheets as supplied by the company.

Table 6.9. Properties of CFRP Sheets

Sr. No.	Physical properties	Values
1.	Tensile Strength	3800 MPa
2.	Modulus of Elasticity	240 GPa
3.	Density	1.7 g/cc

6.3.7 Adhesive

The adhesive used for the all the experiments is a compatible epoxy system recommended by the manufacturer. The adhesive used for bonding FRP sheets with concrete is a Zerokor 21 AD, is a compatible epoxy system provided by the manufacturer. It is black pigmented conductive epoxy resin for saturation of MBrace fibre sheet to form in-situ FRP Composite. It is made by mixing base saturant and hardener in ratio 100:40. Mixing of saturant and hardener is done thoroughly for five minutes until components are thoroughly dispersed. No need of adding Graphite Powder as the epoxy used in present investigation is already conductive.

Fig.6.2 Carbon Fibre Reinforced sheet

6.4 DESIGN OF CONCRETE MIX

M30 concrete mix is prepared using Portland pozzolana cement (PPC), fine aggregate and crushed stone coarse aggregate of size 20 mm and 10 mm. The mix is designed as per Indian Standard Guidelines. The ratio of cement: sand: coarse aggregate is 1:2.36:3.72. The water-cement ratio is 0.43 and compressive strength of concrete after 28 days is 36 MPa.

6.5 SPECIMEN PREPERATION

Specimens were blocks of size 300 x 300 x 60 mm with the tendons placed at the centre. To prepare the specimens the tendons were pre-conditioned and then blocks were cast. The detailed procedure is explained in the following section:-

6.5.1 Preparation and Pre-conditioning of Prestressing Strands

Pre-stressing Strands of nominal size 12.7 mm diameter is used in present work. Firstly strands are cut to required length of 600. Each strands is then wire brushed to remove any surface scale .Then they are thoroughly cleaned using Hexane reagent solution and Petrol so as to remove unwanted impurities from the surface of Strands and allowed to air dry. This strand specimen preparation is similar as specified in *ASTM G 109*. Before casting of the test specimens, each strand is weighed to 0.1 gm accuracy.

6.5.2 Preparation of Block Specimen

In the present program, a special moulding system is fabricated for casting the specimens. The slabs are cast in mould of size (300 x 300 x 60) mm with prestressing tendons placed concentrically. First of all the interior of slab mould is oiled, so that the slabs can be easily removed from the mould after 24 hours. While embedding these strands in concrete, they are kept in such a way that 150 mm lengths of these tendons is protruded outside of the concrete specimen from both sides. When the tendons have been placed in position, concrete mix is poured and vibrations are given so that the mix gets compacted. The vibration is done until the mould is completely filled and there is no gap left. The slabs are then removed from the mould after 24 hours. After demoulding the slabs are cured for 28 days using jute bags. The concrete surface of the slabs is then cleaned and all dirt and loose materials are removed before initiation of corrosion.

6.6 INDUCING CORROSION

The objective of inducing corrosion to the Strand is to simulate the corrosion damaged reinforced concrete. The commonly used methods of inducing corrosion in RC specimens can be recalled as salt spray (*Berver et al. 2001; Debaiky et al. 2002; Batis and Rakanta 2005)*, chloride diffusion *(Tamer et al. 2005; Masoud and Soudki 2006; Tamer et al. 2006)*, alternate drying and wetting in salt water (Debaiky et al. 2002 and Soudki 2006) and impressing anodic current (*Lee et al. 2000*; *Tamer et al. 2003; Wootton et al. 2003, Gadve et al. 2009*). In the salt spray technique a mist with dissolved sodium chloride is created in an enclosed chamber containing the specimens. Previous studies have shown that test specimens kept in a salt spray chamber for more than 100 days did not show any visible signs of corrosion. This method was not found suitable considering the time constraint. Method of adding chlorides artificially to the concrete during casting is an effective method of initiating corrosion in an embedded strand. However this method was not considered because it did not simulate the present condition of interest. Alternate immersion into NaCl (Sodium Chloride) solution and drying of the specimens also induces corrosion. However, the quickest method of inducing corrosion is by impressing anodic current. In this method, the specimen is immersed in NaCl solution and a direct current is passed making the prestressing strand as an anode and another metal nobler than steel in electro-chemical series as cathode. Incidentally, Impressed Current method is used in the present study to induce Corrosion *(Bonacci 2000; Craig 2002; Gadve et al. 2009).*

Impressed Current Technique for Inducing Corrosion

In this investigation, the specimens are kept fully saturated by continuously dripping with 5% NaCl solution as shown in **Fig 6.3**. Mats are placed over the tops to provide even distribution of NaCl solution. The strand is used as anode. A stainless steel (SS) mesh is rolled around 300 mm length of specimen and tied together with metal ties in order to assure electrical continuity is used as cathode. The strand extended 150 mm on both sides past the concrete to allow easy access for making electrical connections to the strand. The constant voltage of 5 mV is impressed in order to accelerate corrosion. The DC regulated power supplier (DCRPS) used in the present study could supply 1000mA DC at 30V. **Fig. 6.4** shows the power supply used to accelerate corrosion in strands. Strand is connected to the positive terminal of the external DC source and negative terminal is connected to the SS mesh. It is more common to maintain a constant voltage between the cathode and the anode *(Soudki 2007; Gadve et al. 2009).* The Electrochemical Techniques viz. half-cell potential and linear polarization measurements are used for monitoring corrosion and the readings were obtained daily for all the specimens throughout the duration of experiment. The techniques are discussed briefly in the following sections.

Fig. 6.3 Block Specimen subjected to 5% NaCl Solution

Fig. 6.4 Power supply used to accelerate Corrosion in specimens

6.7 CORROSION MONITORING TECHNIQUES

Corrosion of pre-stressing strands embedded in concrete is not visually evident until the damage reaches to the external signs of deterioration as rust spots, cracks or spalling. In order to predict the corrosion service life of reinforced concrete structures and to determine the need of repair or rehabilitation, it is necessary to use non-destructive techniques for assessing the corrosion activity and measuring the corrosion rate of the strands. In the present study, the corrosion rate of strands is monitored by electrochemical techniques.

The electrochemical measurements are carried out using a versatile instrument (Make ACM, model: serial no.1463 field machine) that is capable of performing various electrochemical tests such as potential measurement, AC impedance technique, potentiostatic cyclic sweep test, LPR measurements etc. **Fig 6.5** shows ACM setup used for electrochemical monitoring**.** The instrument is capable of processing the data and plotting the outputs automatically.

Fig.6.5 ACM Corrosion Analyser Field Machine

The half cell potential measurement gives only an indication of the corrosion risk of the strand and is linked by empirical comparisons to the probability of corrosion. Therefore along with half cell, linear polarisation (corrosion rate) measurements are taken which provides a valuable insight into the instantaneous corrosion rate of the strand, giving more detailed information than a simple potential survey. The LPR data enables a more detailed assessment of the structural condition and is a major tool in deciding upon the optimum remedial strategy to be adopted. Hence the two important electrochemical techniques that are used for the studying the corrosion activity are corrosion potential (Ecorr) and corrosion current /current density (Icorr). These determining parameters indicate the corrosion initiation which account for strand surface condition and the chloride ion concentration in concrete *(Pradhan and Bhattacharjee 2009; Bhavneet 2010).*

6.7.1 Half cell Measurement

In the present study, all the specimens are monitored daily by half-cell potential using a saturated calomel reference electrode by placing the electrode on top surface of the concrete. The procedure followed is ASTM Standard C 876. The power supply is switched off one hour before taking the half cell readings in order to completely depolarize it. To maintain a consistent testing environment over the 30-day experimental test period, the dripping salt water is replaced daily, electrodes are cleaned daily and the wiring and electrical connections checked twice a day. If the corrosion potential reading is more positive than -200mV, probability is that no pre-stressing strand corrosion is occurring in the area at the time of measurement and if the potential reading is more negative than -426mV, probability is that the strand corrosion is occurring. The experimental arrangement for half cell measurement is shown in **Fig. 6.6.**

6.7.2 Linear Polarization Resistance (LPR) Measurement

Electrochemical LPR technique is especially good at measuring the localized corrosion. LPR measurements on concrete surfaces are performed using guard ring that is supplied with the field machine for precise location of strands. The Guard Ring simply connects to the front panel via the supplied cables. Incorporated into the Guard Ring is a Cu/CuSO4 reference electrode. Before performing the test, conducting sponge is wetted with NaCl solution and placed on the surface of the slab specimen to have proper electrical contact with the guard ring. Guard ring assembly is then placed above the wetted sponge. The electrical connections are made to the pre-stressing strands.

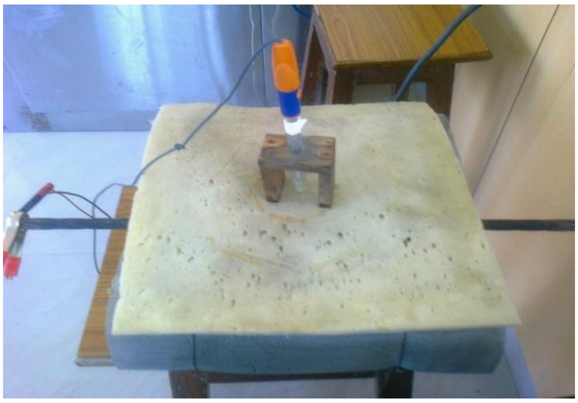


Fig.6.6 Half cell measurement on block specimen

For linear polarization resistance measurement, the working electrode i.e. the strands are polarized to ± 20mV from the equilibrium potential at a scan rate of 0.1mV per second. The experimental arrangement for LPR measurement with guard ring arrangement is shown in **Fig. 6.7**. The polarized surface area of the pre-stressing strands are taken to be that lying under a circle intersecting the midpoint between the two sensor electrodes and only the top half surface area of the pre-stressing strand is assumed to be polarized.

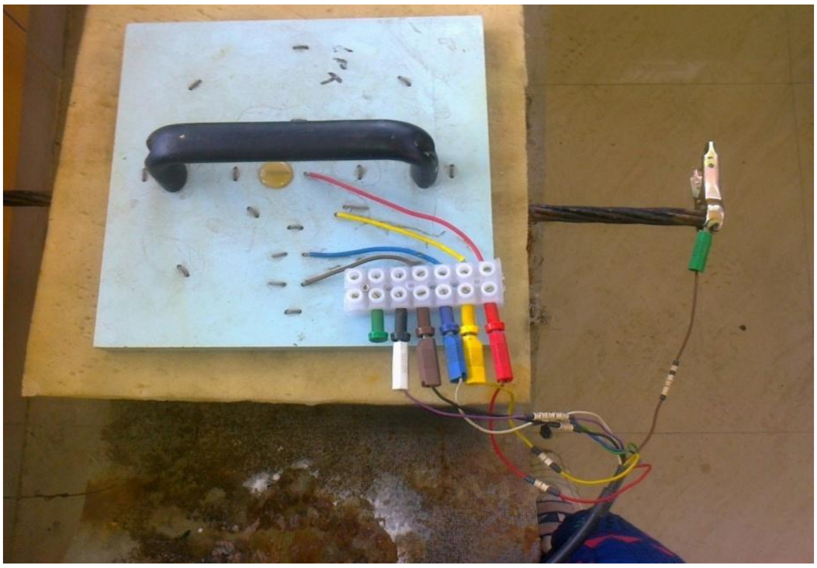


Fig. 6.7 LPR measurement on block specimen with concentrically placed strand

For calculation of the corrosion current density I_{corr}, Stern-Geary equation is used; (*Song and Saraswathy 2007*)

$$\mathbf{I}_{\mathbf{corr}} = \frac{B}{Rp} \tag{6.1}$$

Where, B is the Stern-Geary constant and is given by B = (βa ×βc) /2.3(βa +βc). βa and βc are anodic and cathodic Tafel constants respectively. The value of B is taken as 26mV considering steel in active condition. Rp is the polarization resistance.

6.8 WRAPPING OF PRE-CORRODED SPECIMENS

Two fibre materials are popular in the rehabilitation of structures in India-glass and carbon. Although carbon scores higher than glass in terms of strength, stiffness, durability and fatigue resistance, cost often compels use of glass fibres in structural rehabilitations. The electrical resistance of GFRP is higher than that of CFRP, which might be beneficial in passive resistance to corrosion. However, electrically conductive carbon fibre sheets offer a possibility of cathodic protection of the structure. So in present investigation only CFRP sheets are used as wrapping material.

6.8.1 Method of Applying Wraps

The samples are air dried prior to the application of FRP wraps. Manufacturer's specifications are followed in the application of the wraps. A grinder is used for rounding off the sharp corners and removing local unevenness from the surfaces as shown in **Fig 6.8**. A Wire Brush is used for roughing of slab surface so as to have proper bond between slab surface and epoxy. Conductive Epoxy is used in present thesis for wrapping the carbon fibre sheets onto concrete. It was supplied by Company and is allowed to mix in ratio of 100:40. **S**ince the epoxy adhesive used is electrically conductive, therefore addition of graphite powder is avoided.

FRP Sheets used for wrapping is unidirectional. 300 mm length of CFRP Sheet is wrapped throughout the test specimens and an overlap of 50 mm is provided at the ends of the sheets. This CFRP wrapped test specimen is additionally provided with adhesively bonded 25-30 mm wide carbon ribbon so that uniform distribution of direct current throughout the specimen is possible for effective application of active protection. **Fig 6.9** shows Epoxy applied concrete surface with carbon ribbon.

Fig.6.8 View of grinder

Fig.6.9 Epoxy applied on concrete surface of slab

Sufficient pull is applied to the fibre sheet to ensure uniform direction of fibre and absence of wrinkles as shown in **Fig. 6.10.** Care is taken to avoid air gaps between the concrete surface and the confining carbon fibres. So, plain rod is rubbed for smoothening on top surface of CFRP sheet as shown in **Fig. 6.11.** So that the sheet makes uniform bond with epoxy. **Fig 6.12** shows CFRP wrapped on concrete surface, making uniform bond with epoxy. All the wrapped specimens required one day to cure.

Fig.6.10 Placing CFRP sheet

Fig.6.11 smoothening of surface

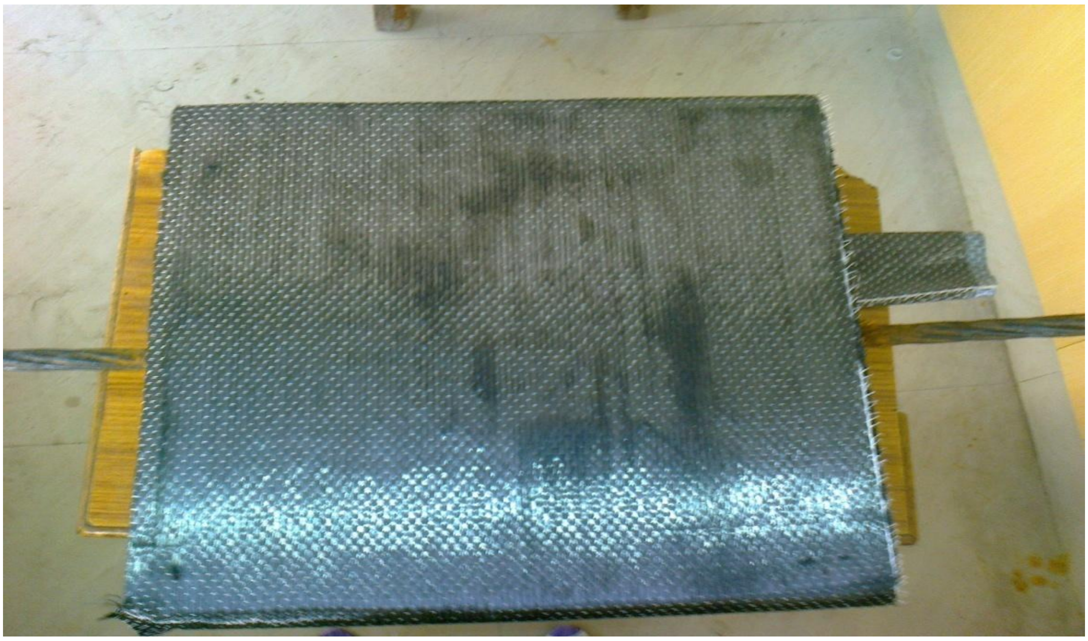


Fig.6.12 FRP wrapped on concrete surface

6.9 ACTIVE PROTECTION

Active protection is a technique which aims at stopping rebar corrosion in chloride contaminated concrete. The alkalinity of the concrete around the strand is restored, and an environment favourable to the passivation of strand is re-created. The technique is based on the application of a DC current in which the prestressing strand acts as cathode and CFRP sheets wrapped on the external surface of the concrete are used as anode. It is an electrochemical process, exactly opposite to that of corrosion process, which also involves anode, cathode and electrolyte.

6.10 CORROSION OF WRAPPED SPECIMENS

Objectives of our present study are to investigate the effect of impressed current for active protection. To simulate corrosion damaged structures, prior to the application of wrap an initial exposure is applied. The time of exposure was adjusted so as to have three levels of damage viz. onset of corrosion, onset of visible crack, and 2 days after onset of visible crack are applied. After corrosion the specimens are wrapped with FRP sheets and a constant anodic current of 10 mA is supplied with CFRP sheet as anode and tendon as cathode. Specimens for Active Protection is shown in **Fig 6.13**, in which positive terminal are connected to the carbon fibre ribbon and the negative terminal is connected to the prestressing strand**.** Corrosion monitoring is done as explained earlier using half cell potential and LPR measurements for a period of 30 days. For comparison, three specimens are kept under passive protection in which they are corroded to the levels explained earlier and then wrapped with CFRP Sheets. No current is applied between the sheet and the tendon. The specimens are shown in **Fig. 6.14**. The monitoring procedure is similar to the one explained earlier.

Fig.6.13 Set up of slab specimens for Active Protection

Fig. 6.14 Set up of Block Specimen for Passive Protection

6.11 CONCLUDING REMARK

In this chapter, procedure for monitoring corrosion of prestressing strands by various methods is discussed in detail. Complete picture of changing condition of structure with time is given by Corrosion Monitoring. Therefore properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could affect enormous saving. Care should be taken during wrapping of CFRP sheet which is also discussed in detail.

CHAPTER 7

RESULTS AND DISCUSSIONS

In this chapter, the findings of the experimental investigation are presented, wherein various corrosion tests have been conducted to evaluate the performance of FRP wrapped specimens actively protected against corrosion.

7.1 GENERAL

There are a number of techniques that can be used to carry out assessment of a structure suffering from corrosion of the strand *(Broomfield, 2002).* However, in order to determine the rate of deterioration of the structure, it is useful to monitor the condition change with time. The objective of our present study is to investigate the efficacy of active protection with CFRP composites used for the repair of corroded reinforced concrete slabs. First, the slabs are subjected to acceleration corrosion process to initiate corrosion. They are then repaired and actively protected so that corrosion of strand can be avoided. Monitoring is done using two test methods, namely half cell potential and Linear Polarization Resistance (LPR)

7.2 ELECTROCHEMICAL MEASUREMENTS

7.2.1. Half Cell Potential Measurements

Half-cell potential (E_{corr}) of pre-stressing tendons in all the nine slabs is recorded everyday throughout the duration of experiment. Saturated calomel electrode is used as a reference electrode. The specimens should be depolarized before taking the Half Cell Potential reading, in order to measure the electrochemical signals correctly. The current is interrupted for one hour to achieve this purpose, prior to the measurement of the half-cell potential. The major objective of our study is to investigate the effect of applied current during active corrosion protection and passive corrosion protection on behaviour of slabs. 10 mA (40 $\mu A/cm^2$) of current are chosen for this purpose for all 6 slabs. **Fig. 7.1** shows variation of half cell potential during the test period for three block specimen subjected to passive protection. **Fig. 7.2, Fig. 7.3, Fig. 7.4** shows the variation of half cell potential during test period for six block specimen subjected to active protection.

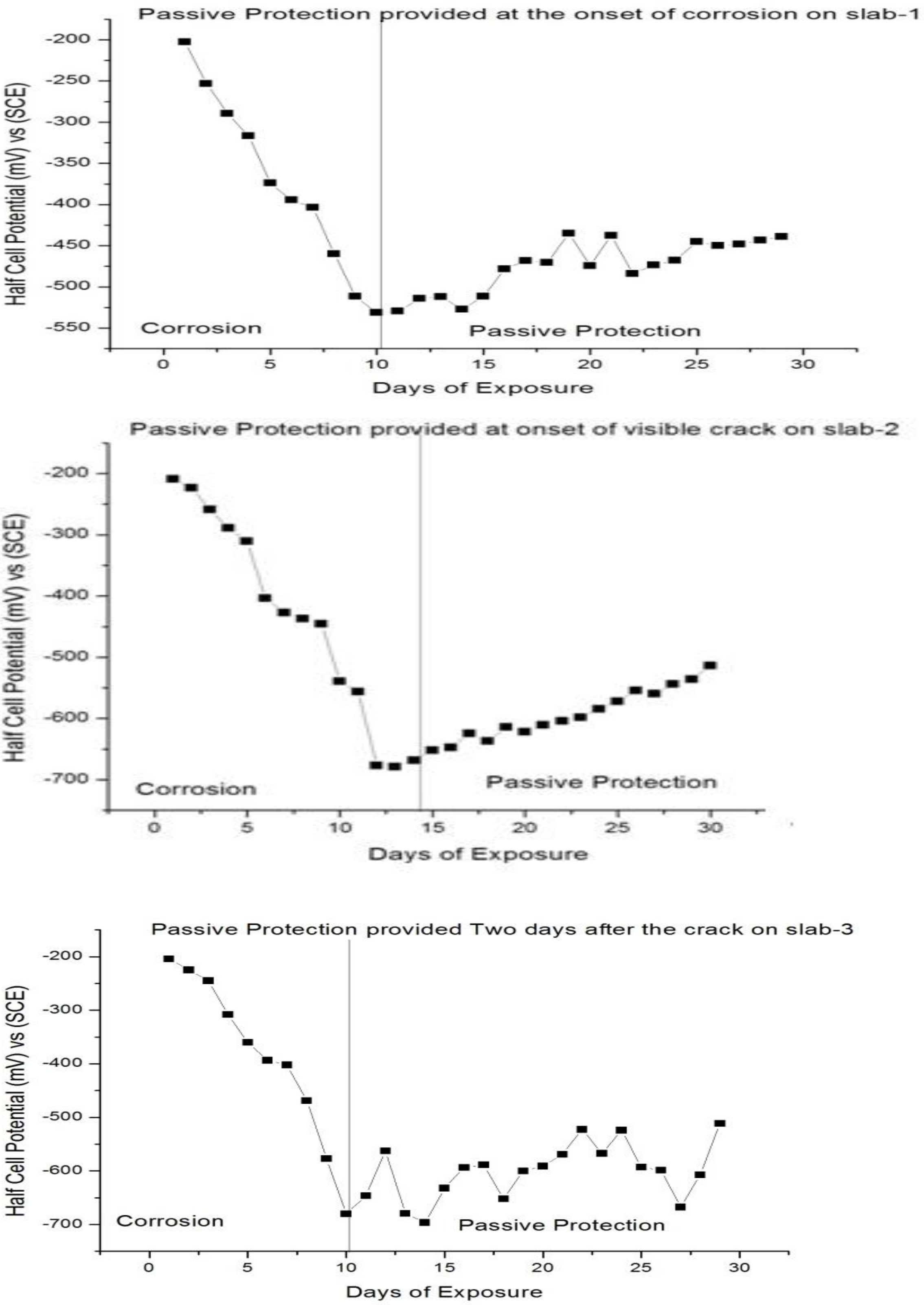
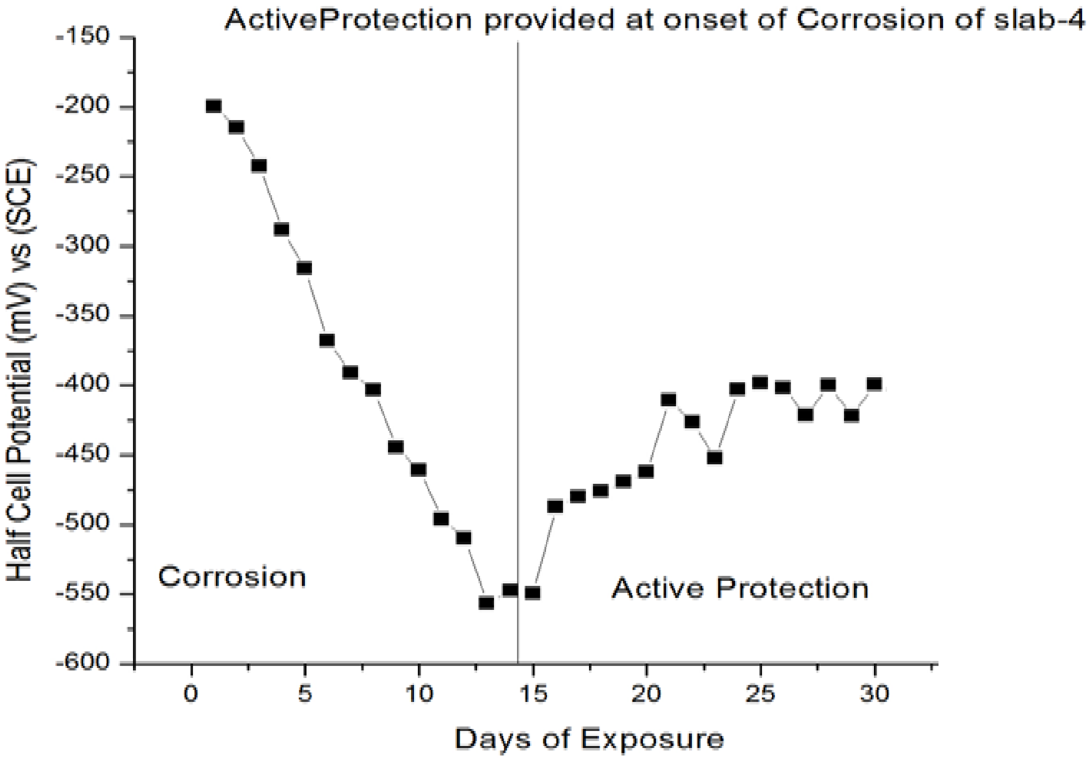


Fig. 7.1 Corrosion and Passive Protection provided on block specimen at three stages of corrosion by Half Cell Measurement



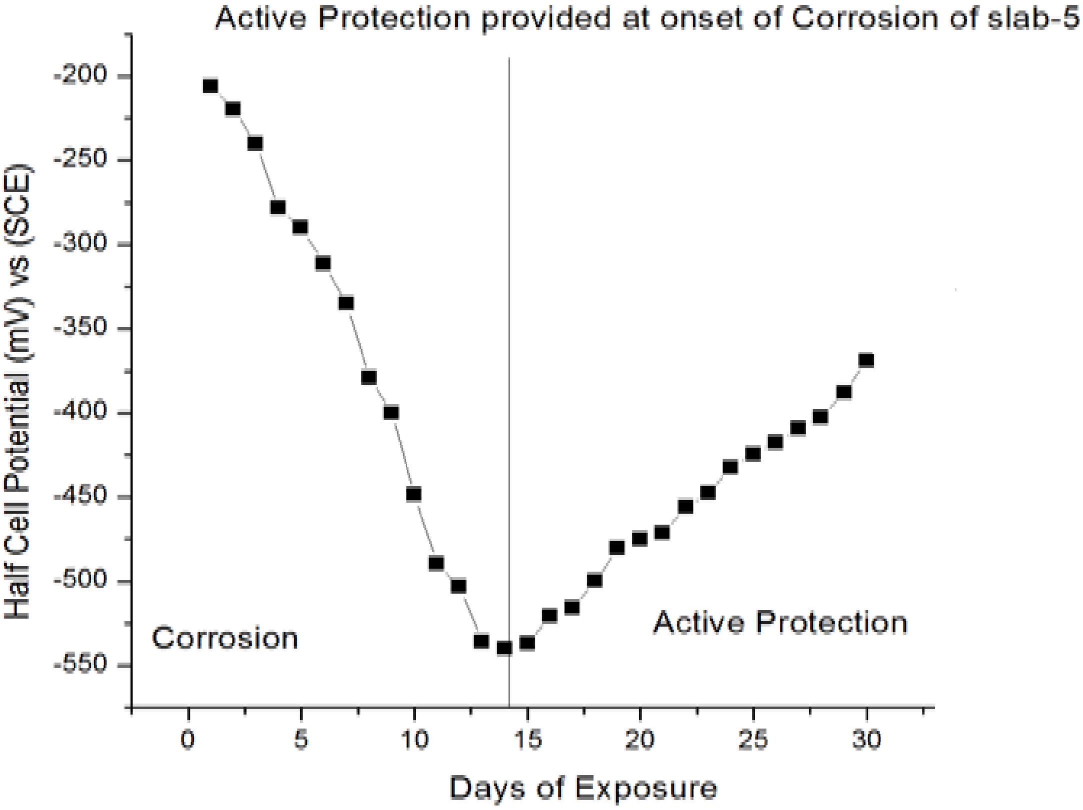
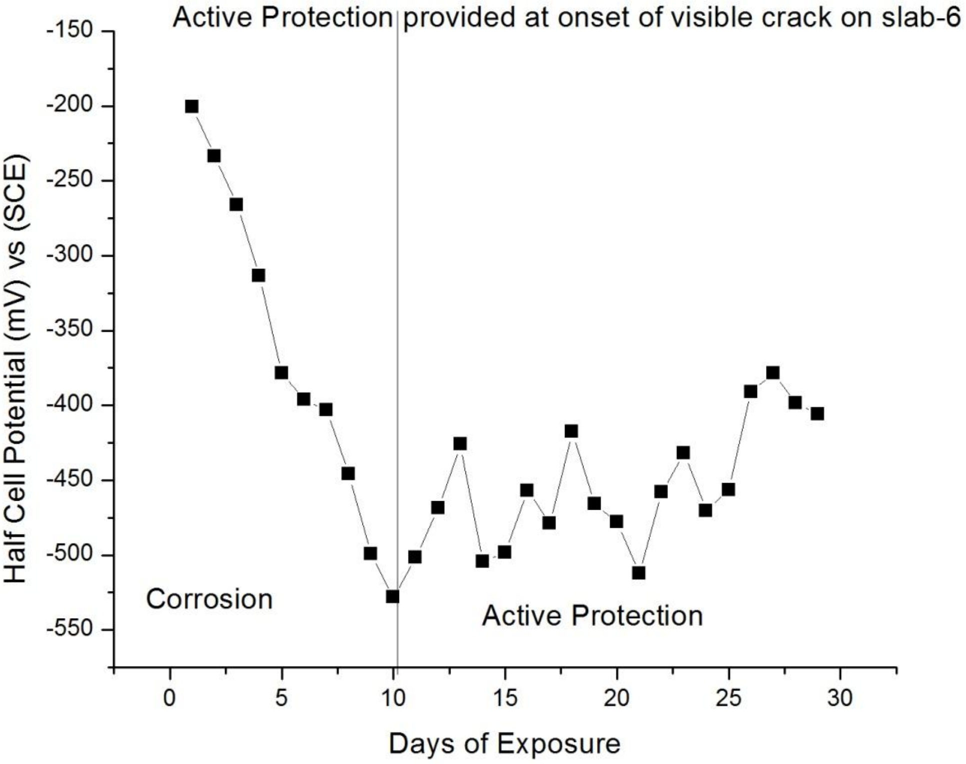


Fig. 7.2 Corrosion and Active Protection provided on block specimen at onset of Corrosion by Half Cell Measurement



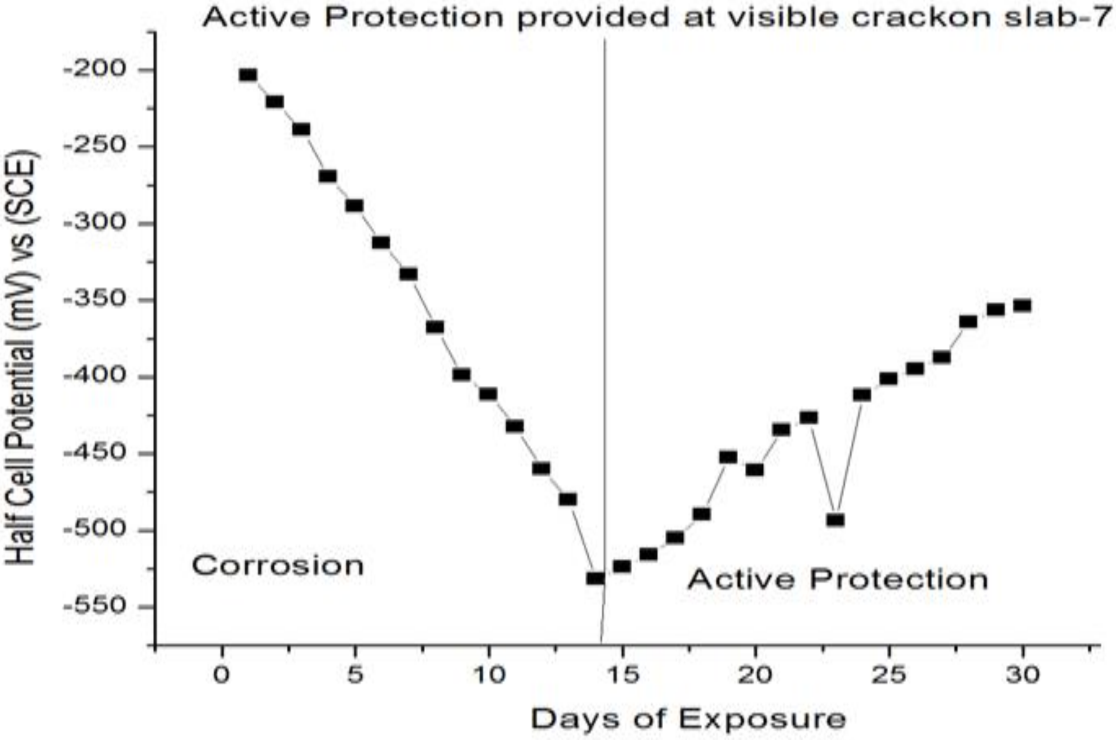
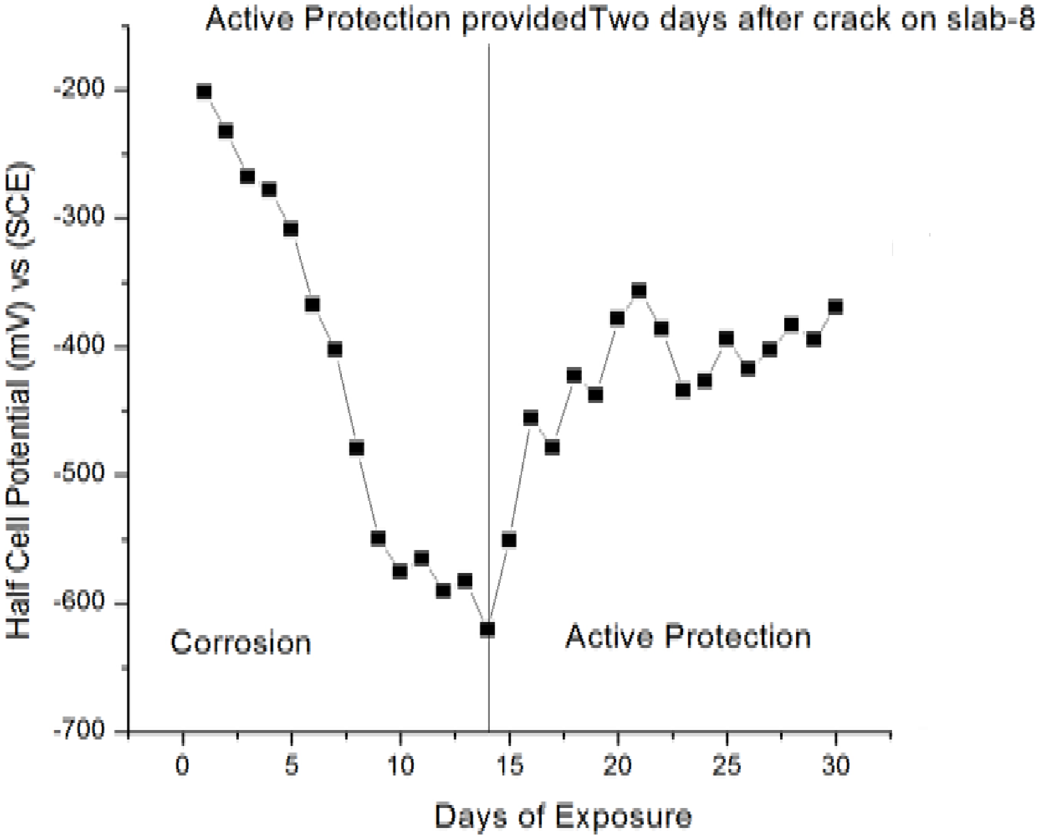


Fig.7.3 Corrosion and Active Protection provided on block specimen at the onset of visible crack



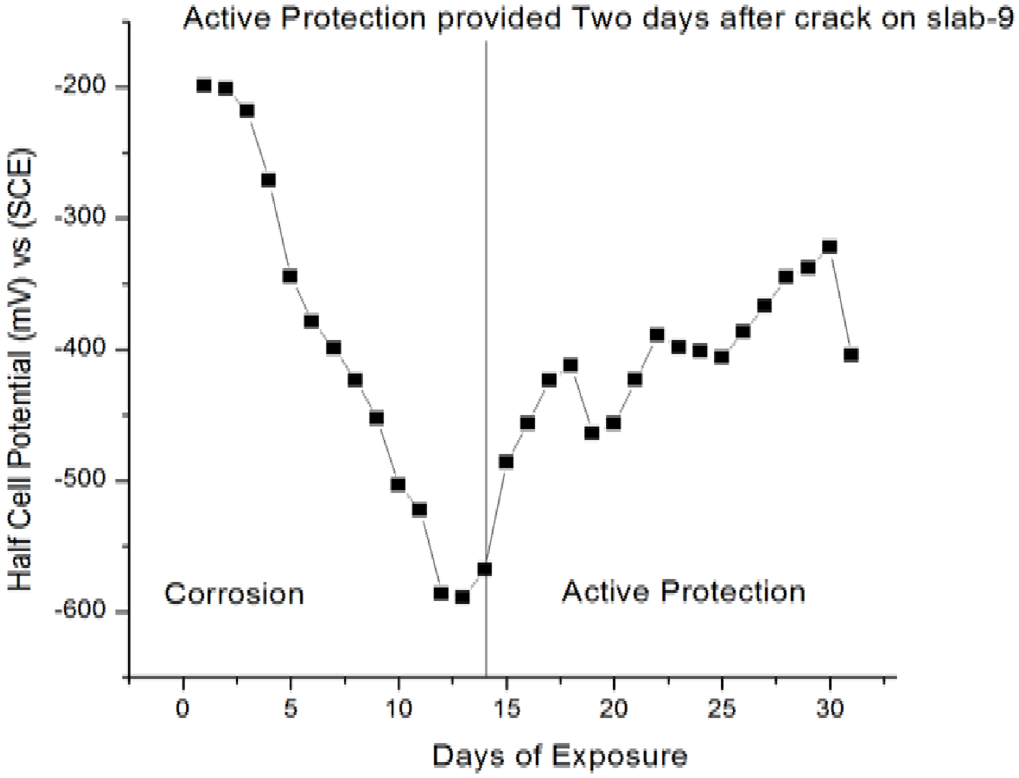


Fig.7.4 Corrosion and Active Protection of Block Specimen Two days after crack

OBSERVATIONS

Establishing structures potential map, according to ASTM C876-91, is the most commonly applied electrochemical technique for diagnosing the corrosion risk of reinforced concrete structures *(Pradhan and Bhattacharjee (2009); Saidy et al.(2010))*. ASTM C876-91 suggests that the corrosion possibility of rebar embedded in concrete is higher than 90% when the open circuit potential is lower than -426 mV (SCE). From the experimental results, it is observed that the half cell measurements keep on varying with time but within a certain defined range. In the initial stages of corrosion acceleration, the half cell potential values are less than the corrosion threshold values i.e -426 mV, which indicates that corrosion has not started yet. Then the values kept on decreasing towards the more negative side indicating depassivation of strand, until it reached a stage of severe corrosion. This rate of drop is nearly uniform for all specimens. With the passage of time longitudinal cracks appeared along the length of the strand as shown in **Fig. 7.5**

Fig. 7.5 Longitudinal crack along the length of Strand

The reason behind this is due to the formation of corrosion products around the strand that occupies volume larger than the original volume of the strand, causing bursting stresses in the concrete. This indicates that corrosion has caused enough strand cross section loss and the structural capacity of the element is significantly impaired. The occurrence of longitudinal cracking if not repaired may often be precursors to more critical and dangerous situation. That is why retrofitting of slabs is required at this stage.

From the results, it is observed that, there is sudden drop in half-cell potential of the strand specimens after a certain interval of time. This indicated that a certain amount of chloride has reached the pre-stressing strand as expected and is responsible for the corrosion initiation as it has become anodic.

However, after providing active protection in six slab specimen i.e. after wrapping and providing impressed current of 10 mA, the half cell value rises slowly, in all the specimens irrespective of time of wrapping and applied current. It indicates that FRP did serve as an effective barrier for chlorides and prevented corrosion activity from taking place to some extent. Similar observations were made by *Nimrat et al.(2011)* for FRP wrapped samples. However, the E_{corr} value of specimens is still in the state of active corrosion and will require some more time to reach passive stage. Therefore, in order to fully evaluate the effectiveness of FRP composite wrap in corrosion prevention, long-term testing is required on specimens that have been adequately repaired.

Moreover after providing Passive Protection in another 3 slab specimens i.e. after wrapping with FRP sheet only without allowing Impressed current to pass through slabs, indicates that FRP did serve the purpose as an effective barrier to corrosion activity, but passive protection provide extremely slow recovery from corrosion, which can be seen from **Fig.7.1.** The half cell potential values slowly reaches to less negative potential in the case of passive protection by FRPs.

From above two protection methods, we can conclude that Active protection provide sufficient and adequate recovery from Corrosion on slabs, while Passive protection with FRP sheets arrest the further corrosion but did not recover much from corrosion as compared to Active protection.

7.2.2 Corrosion Rate by LPR Technique

LPR measurements are necessary as the values obtained from corrosion current density (I_{corr}) indicate the progression of corrosion in the propagation phase. This method is more reliable than Half-cell method as Half cell method indicates only probability of corrosion initiation in slabs. *Feliu et al. (2004)* found that E_{corr} depends on the degree of wetness of the concrete to a great extent. *Xu and Yao (2009)* concluded that the corrosion state of strand in chloride containing and chloride-free structures tends to be confused if the decision is based exclusively upon the E_{corr} values as shown in **Fig. 7.6**.

Fig. 7.6 shows variation in corrosion current density (I_{corr}) during the test period for three block specimen subjected to passive protection by LPR method. **Fig. 7.7, Fig. 7.8 and Fig. 7.9** shows variation in corrosion current density (I_{corr}) during the test period for six block specimen subjected to active protection at the onset of corrosion, onset of crack and two days after crack respectively, by LPR method.

OBSERVATIONS

Corrosion current density (I_{corr})determination by LPR method indicate that the corrosion current density (I_{corr}) increased with days of exposure to applied voltage due to increase in chloride concentration around the strands in all the specimens. As the corrosion progresses in the slabs the value of corrosion current (I_{corr}) rises. This is because of the depassivation of layer formed around the strand due to the concentration of chlorides (NaCl). From the **Fig. 7.6, Fig. 7.7, Fig. 7.8, Fig. 7.9** it is concluded that during the acceleration process, the I_{corr} values are between 7 – 10 $\mu A/cm^2$ which indicates low corrosion. As we are increasing the exposure value the I_{corr} rises upto 25 $\mu A/cm^2$ which indicates moderate corrosion. Further as the exposure value increases, I_{corr} reaches 35 $\mu A/cm^2$ which indicates major corrosion and crack is observed. Similar observations were made by *Martínez and Andrade (2009).*

However, after active protection i.e. wrapping with CFRP sheet at three different stages of corrosion as mentioned earlier, the value of I_{corr} starts decreasing and corrosion risk is coming down from high to moderate. This trend is common irrespective of level of retrofitting. *Koleva et al. (2006)* applied active protection by passing direct current to steel reinforcement and observed that corrosion current density decreases as the period of exposure increases. Lower I_{corr} for the wrapped samples establishes that wrapping significantly reduces the rate of corrosion. Similar observations were made by *Gadve et al. 2009)* in which the FRP wrapped samples had lower I_{corr} than the control sample.

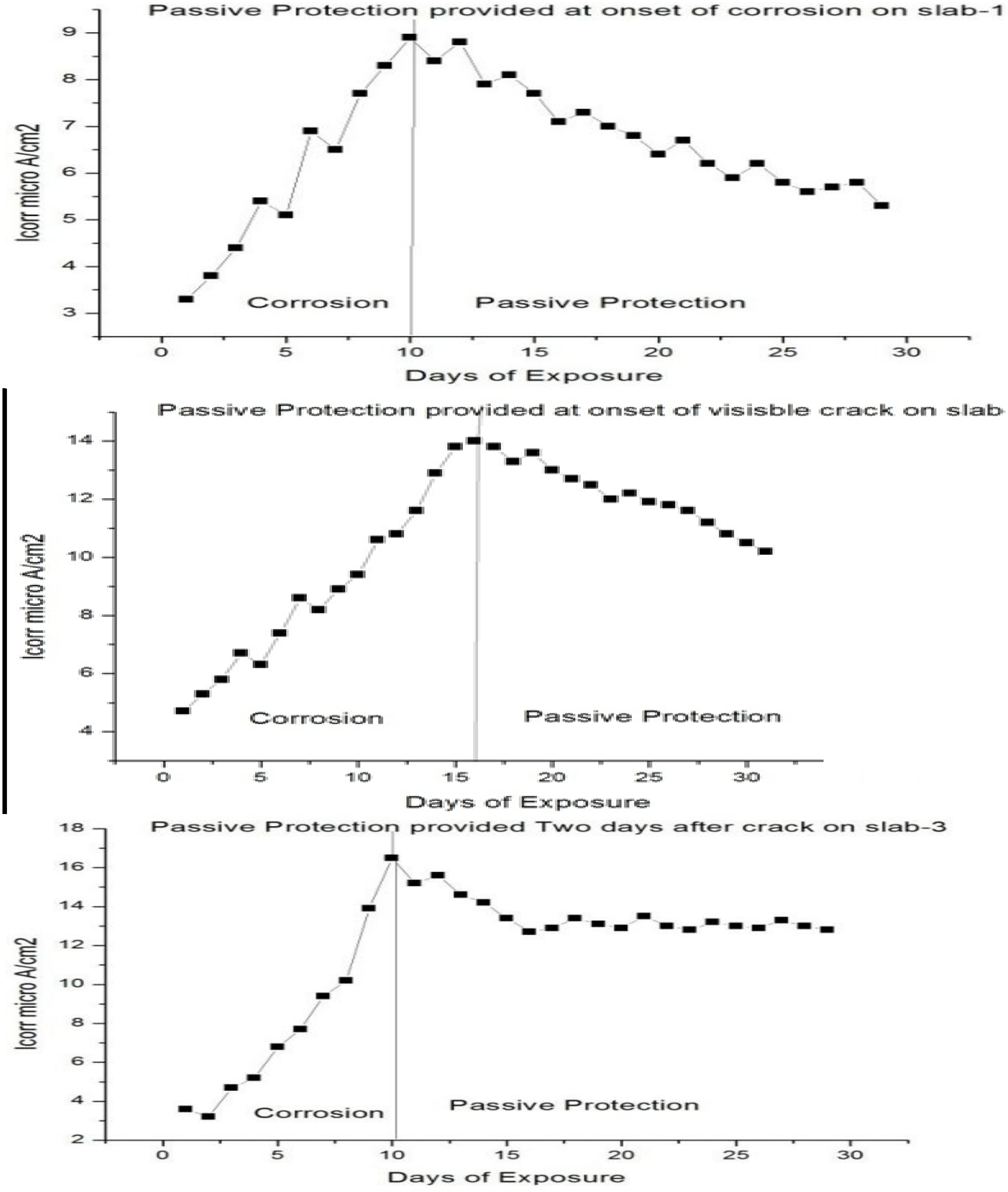


Fig. 7.6 Corrosion and Passive Protection provided on block specimen at Three Stages of corrosion by LPR Method

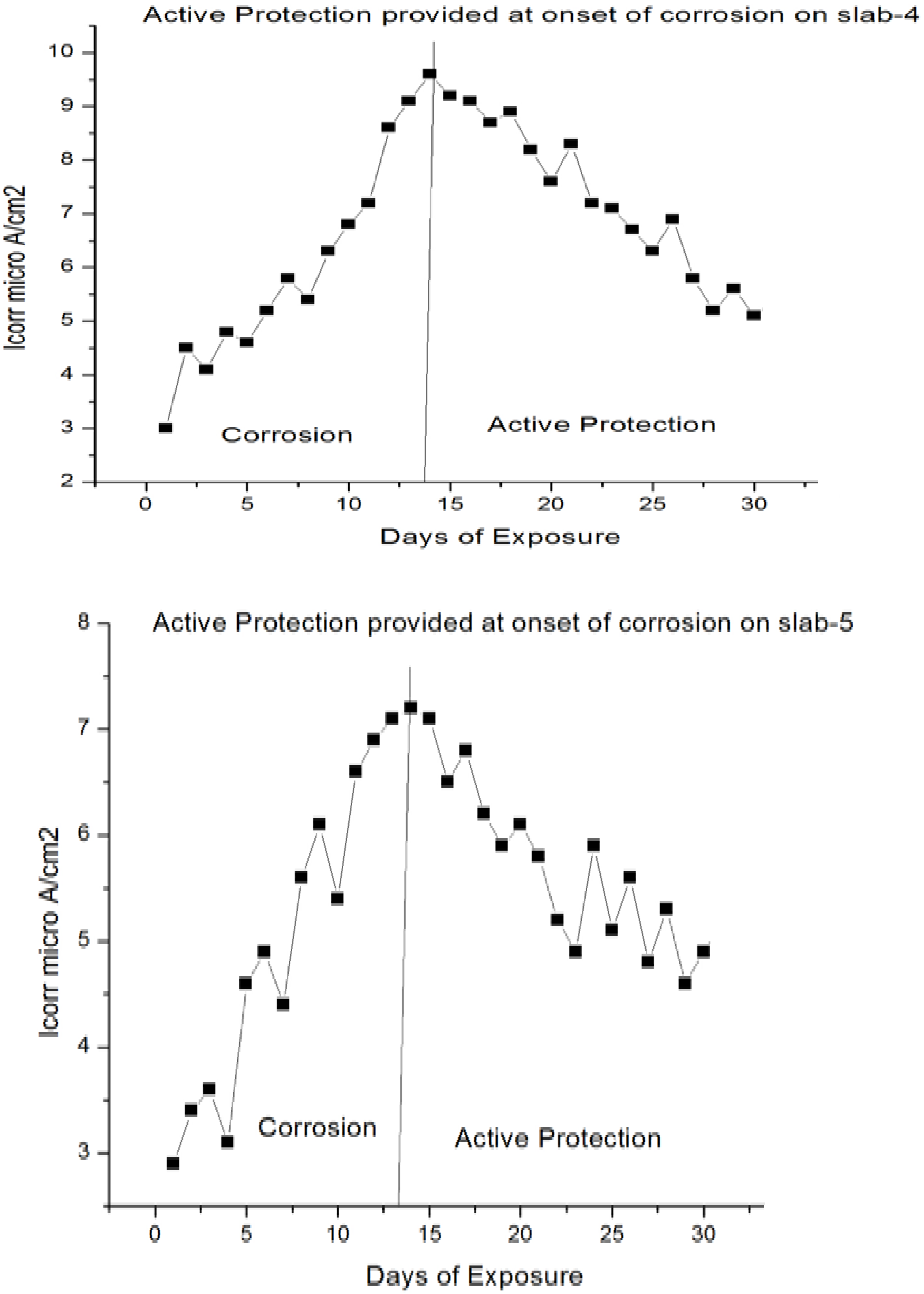
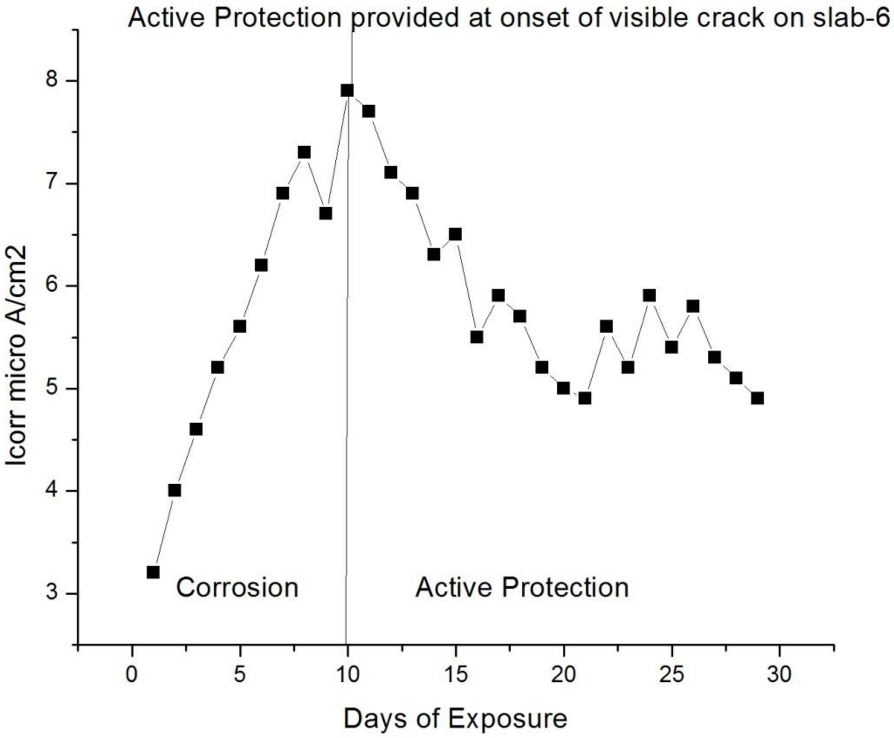


Fig. 7.7 Corrosion and Active Protection provided on block specimen at onset of corrosion by LPR Method



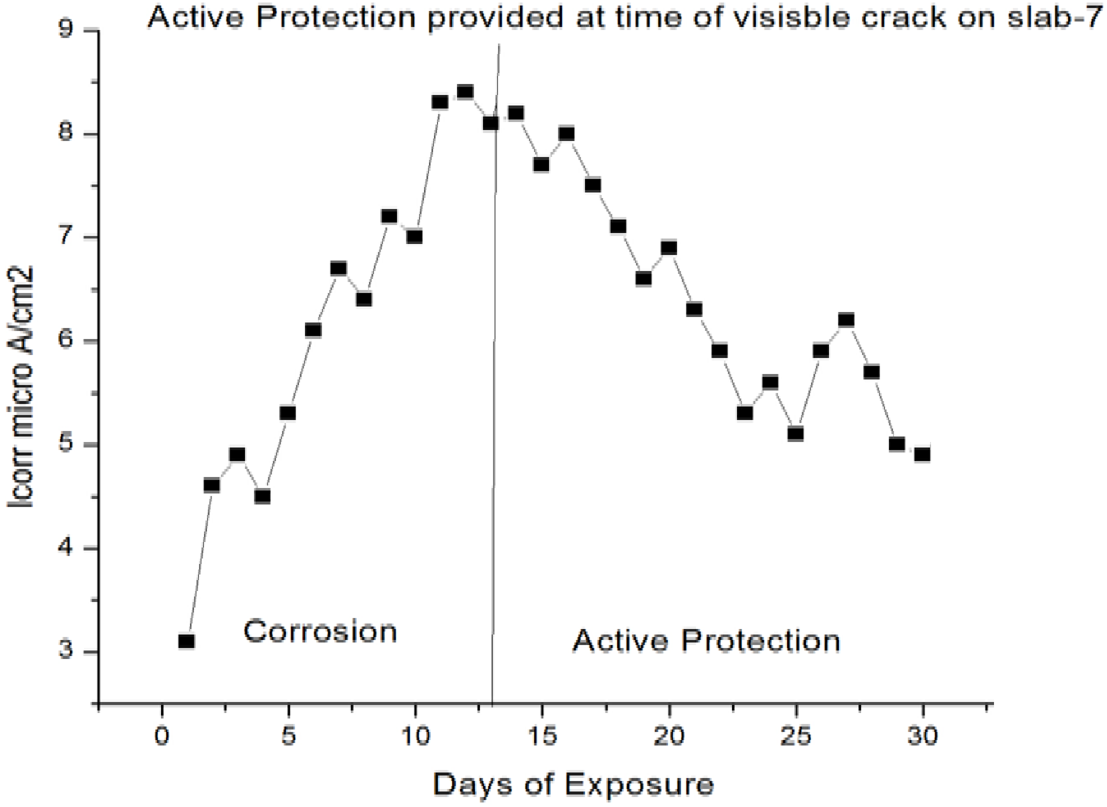
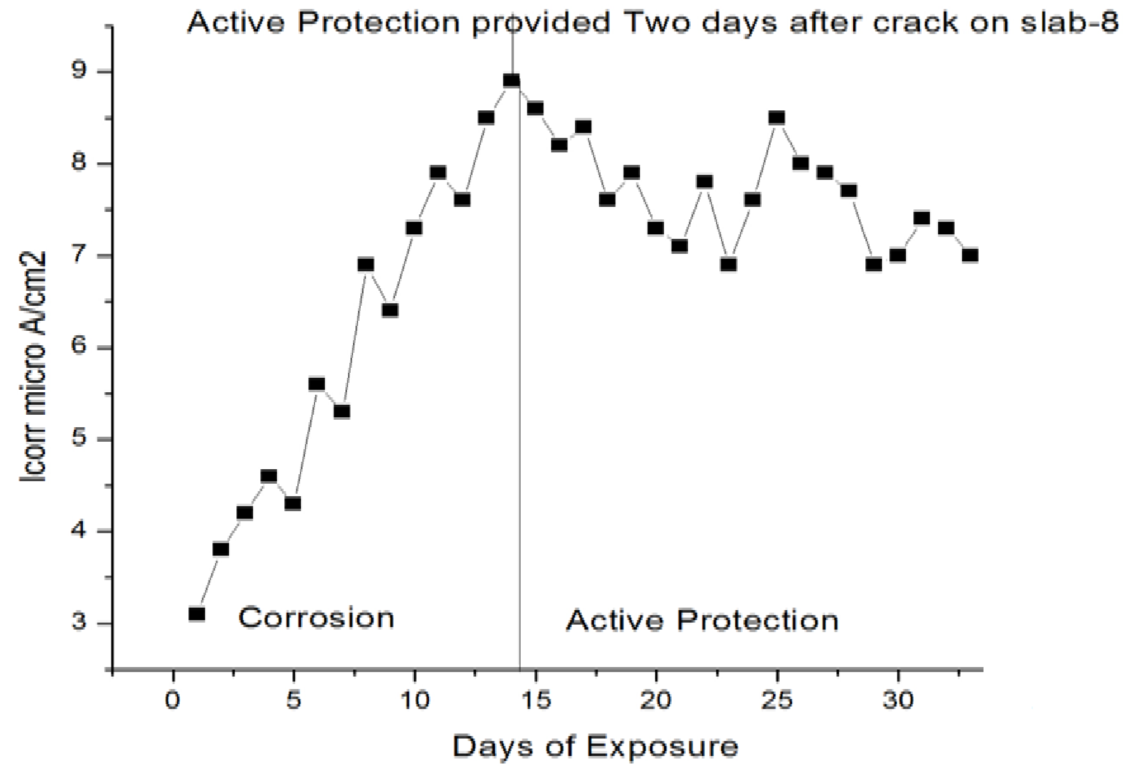


Fig. 7.8 Corrosion and Active Protection provided on block specimen at the time of visible crack by LPR Method



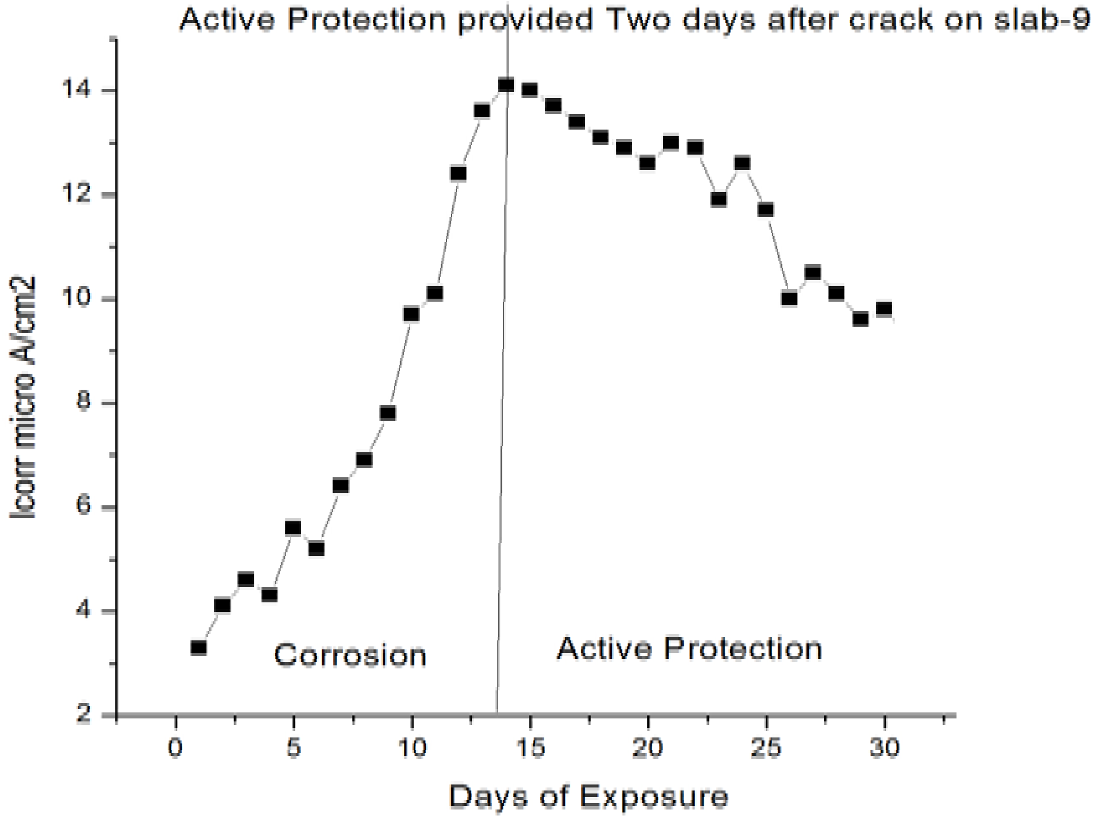


Fig.7.9 Corrosion and Active Protection provided on block specimen, Two days after crack by LPR Method.

During Passive Protection provided to slab specimen wrapped only with FRP Sheets subjected to different stages of corrosion namely (i) onset of corrosion, (ii) onset of visible crack and (iii) two days after onset of visible crack, values of corrosion current density are constant after protection or are decreasing at very slow rate, with the values remaining almost at the same level at which protection was provided. One the other hand active protection lowers the corrosion current at the faster rate. However the final I_{corr} values has not yet stabilized after 30 days of monitoring and the specimens are to be protected and monitored further. **Table 7.1** shows Corrosion condition at different values of I_{corr}.

On comparing further the protection of tendon with the protection of rebar (work done by *Nimrat (2011)*), it is observed that the rebars are protected more effectively as compared to tendons. In rebars, the I_{corr} values came in very low corrosion stage within 30 days, as opposed to tendons, in which I_{corr} values are still in moderate corrosion stages.

Table 7.1 Corrosion condition at different values of Current Density

S.No.	I_{corr} (μA/cm^2)	Corrosion Condition
1.	7-10	Low Corrosion
2.	Upto 25	Moderate Corrosion
3.	35	Major Corrosion with Crack

7.3 CONCLUDING REMARK

The test results showed that although CFRP sheet wrapping decreased the corrosion rate by both active protection and passive protection. However, active protection is very effective in decreasing corrosion rate. However, long term monitoring is required in order to completely eliminate the corrosion activity.

CHAPTER 8

CONCLUSIONS

MAIN CONCLUSION

The results obtained from the tests, carried out in the present research work for evaluating the corrosion performance of corroded specimens wrapped with FRP are presented in this chapter. From the results it is concluded that**:**

- CFRP can be used effectively in providing active protection to reinforced concrete structural components by using carbon wrap itself as anode and the tendon as cathode.

- The protection current could modify the material structure to a favourable trend in terms of corrosion protection and prevention.

- It is observed that active protection reduces the rate of corrosion in concrete block specimens exposed to an aggressive chloride environment to a greater extent.

- LPR method is more reliable technique used for monitoring as compared to Half cell method.

- Actively Protected block specimen’s shows better corrosion protection with time irrespective of time of wrapping as compared to passively protected block specimen.

- Both electrochemical techniques (LPR and Half-Cell) measurements are efficient in monitoring corrosion behaviour of prestressing strands. However, no single technique is capable of providing all information about corrosion behaviour and hence these should be used simultaneously in order to get reliable results.

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