DECLARATION

This is to certify that the project titled“**TO ANALYSE THE EFFECT OF CATHODIC PROTECTION ON R.C.C STRUCTURAL MEMBER**” is a bonafide record of research work carried out by me, (Mohit Rajpal, Roll No. 2K12/STR/11), student of Master of Technology in Structure Engineering (Civil Engineering), Delhi Technological University, Delhi, during the session 2013-2014 towards the partial fulfillment of the requirements for award of the degree of Master of Technology in Structure Engineering(Civil Engineering).

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The above statements by Mohit Rajpal, is correct to the best of my knowledge.

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ACKNOWLEDGEMENT

The success of any project depends largely on the encouragement and guidelines of many others. Therefore I take this opportunity to express my sincere gratitude to the people who have been instrumental in the successful completion of the project.

I would like to express our sincere appreciation and gratitude to my guide Dr. Awadhesh Kumar without whose able guidance, tremendous support and continuous motivation the project would not have been carried to perfection. I sincerely thank him for spending all his valuable time, energies and motivating me to do perform our level best during the execution of project, to inculcate and define our hard work by mode of our project.

The successful compilation of major project depends on the knowledge and attitude inculcated in the total length of course. So I want to express my sincere gratitude to all the faculties who taught us during M. Tech.

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ABSTRACT

Corrosion is one of the most stimulating troublesome phenomenon that steel structures, pipelines and R.C.C structures have to go through , which certainly leads to unsafe structures and cause economical losses which arises in order to control the losses caused by effect of corrosion mainly in areas close to sea bed & explicit Weathering leading the steel and R.C.C structures to go through adverse change in weathering thus as we are aware that sudden changes of weather causes deposition of chloride ions leading to corrosion.

There are methods to safeguard structure temporarily from the effects of corrosion using some basic methods which are effective for small run only like grouting on joints to avoid contact of reinforcement with atmospheric conditions , using special adhesive paints to protect the outer surface of steel structures and using cement slurry with adhesive bonds to protect the reinforcement in R.C.C structures, but the key method to protect the structure and fight corrosion is Cathodic protection.

Cathodic protection is one of the most appropriate world famous method to protect from corrosion , in this method we basically control the flow of ions which is the cause of corrosion , there are two main types of cathodic protection used worldwide one is SACP (Sacrificial anode cathodic protection) and ICCP (Impressed current cathodic protection) . ICCP method is more reliable as compare to the other whether it be more complicated, uneconomical but still it has more preferences due to monitoring and controlling aspects which enables for superior control.

In initial part of project we have tried to show the effect of corrosion on different r.c.c structures having similarities in shape, size but with reinforcement thus we have tried to cover major types of structures by using R.C.C beams , cubes and cylinders with different reinforcement . Using resistivity meter we have tried to check & evaluate change observed in above mentioned r.c.c structures with providing different environmental conditions to few of the samples to see and measure the changes experienced in consideration to aspect of corrosion , the samples prone to adverse environmental condition are then further treated with Iccp using dc supply which enables to eradicate the effect of corrosion for time being .

The different structural members are firstly provided with Iccp to fight back the effect of corrosion individually, then we using different cubes, beams and cylinders in different circuits.To measure the effect of Iccp method in big structures , we have provide the reports of different structures kept in couples with similar or different structures which elaborates the effect of cathodic protection in super structures , the results show the positive effect of cathodic protection on r.c.c structure leading to its use in all major structures.

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CHAPTER-1: INTRODUCTION

Cathodic Protection is a technique used to control the corrosion of a metal surface by making it as cathode of an electrochemical cell. A simple method of protection connects protected metal(cathode) to a more easily corroded "sacrificial metal" to act as the anode. The sacrificial metal then corrodes instead of the protected metal. For structures such as long pipelines, where passive galvanic cathodic protection is not adequate, an external DC electrical power source is used to provide sufficient current.

Cathodic protection systems protect a wide range of metallic structures in various environments. Common applications are: steel water or fuel pipelines and storage tanks such as home water heaters; steel piers piles; ship and boat hulls; offshore oil platforms and onshore oil well casings; and metal reinforcement bars in concrete buildings and structures. Another common application is in galvanized steel, in which a sacrificial coating of zinc on steel parts protects them from rust.

Cathodic protection enables to ensure the longevity to the life of structure by resisting the formation of chloride ions either by method of sacrificial anode (cathodic protection) or by impressed current (cathodic protection) ,basically the life of R.C.C structure depends on the condition of reinforcement that might degrade with time leading to severe losses in strength of structure thus it is of prime importance to govern the effect of corrosion and certainly do the required and follow all parameters to avoid any sort of failure due to corrosion.

The main cause of corrosion is humidity/exposure to water , change in environmental condition and etc , I have tried to show the effect of corrosion on different samples like beams of size (27"x6"x6") , cubes of size (6"x6"x6") and cylindrical cubes (3" dia x5") with the use of different type of reinforcement for example fy 500 , fy 415 ,and corroded bars . After analyzing the effect of corrosion on samples by providing very active environment and providing sudden wet and dry condition with in a very small span which leads to enhanced effect of corrosion.

Further now we have corroded samples of beams, cubes etc along with uncorroded samples , by providing D.C to corroded samples we try to check the effect of corrosion , whether it is decreasing or stand still , with low voltage we could not observe much difference on samples which were on the verge of peak corrosion , but by providing good amount of d.c banofide results could be seen , thus the effect of corrosion become negligible for the time we provided D.C.

To analyze the effect of Impressed Current Cathodic Prrotection on huge structures we tried to join more numbers of samples with similar level or unsimilar level of corrosion leading us to get to the results which somehow were quite similar to a normal big structure for example a building with ten numbers of columns ,beams and slab in which we want to see the effect of cathodic protection on all members by just providing the direct current as per requirement of one member .

DETAIL HISTORY OF CATHODIC PROTECTION

Cathodic protection was first described by Sir Humphry Davy in a series of papers presented to the Royal Society in London in 1824. The first application was to the HMS Samarang in 1824. Sacrificial anodes made from iron attached to the copper sheath of the hull below the waterline dramatically reduced the corrosion rate of the copper. However, a side effect of the cathodic protection was to increase marine growth. Copper, when corroding, releases copper ions which have an anti-fouling effect. Since excess marine growth affected the performance of the ship, the Royal Navy decided that it was better to allow the copper to corrode and have the benefit of reduced marine growth, so cathodic protection was not used further.

Davy was assisted in his experiments by his pupil Michael Faraday, who continued their research after Davy's death. In 1834, Faraday discovered the quantitative connection between corrosion weight loss and electric current and thus laid the foundation for the future application of cathodic protection.

Thomas Edison experimented with impressed current cathodic protection on ships in 1890, but was unsuccessful due to the lack of a suitable current source and anode materials. It would be 100 years after Davy's experiment before cathodic protection was used widely on oil pipelines in the United States[1] — cathodic protection was applied to steel gas pipelines beginning in 1928[1] and more widely in the 1930s.

CHAPTER 2 OBJECTIVES, SCOPE AND METHODOLOGY OF THE STUDY

2.1 Objectives of the study

This study is carried out to evaluate the effect of cathodic protection on R.C.C. structure by use of impressed current cathodic protection. This method enables our study to define the effect of corrosion on r.c.c. structures and the way back by which we can resist the effect of corrosion. This method allows us to provide the strength for which the structure is designed and retain it for long span by protecting it from the action of corrosion , as we know that due to effect of weathering r.c.c. structure suffer from corrosion leading to losses in strength.

Due to environmental factors the climate has become very active in respect of humidity/moisture which is the main cause of corrosion. Due to some pore holes or voids or due to lack of proper cover the reinforcement is exposed to the direct effects of atmosphere leading to active corrosion and to control the effect of corrosion we have used cathodic protection which enables us to resist the effect of corrosion conditionally till the direct current supply is provided or a sacrificial or more active anode is their which can get corroded to avoid the losses to main member.

The main application of Impressed Current Cathodic Protection is to provide electrons which enables to break the flow of corrosion action, as described in the figure1 below.

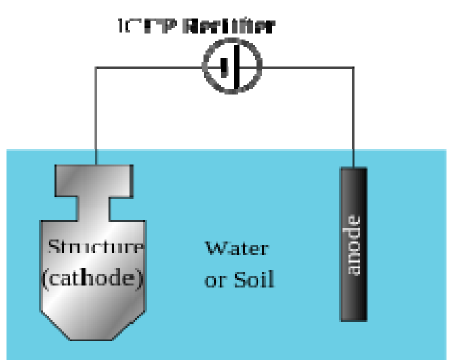

Figure 1.diagram shows flow of ions in impressed current cathodic protection. Refrence [38]

2.2 Scope of the study

1) This study is concentrated to maintain the resistivity of r.c.c. more than 20 kilo ohm per cm so as to resist the effect of corrosion.

2) Different samples of reinforced cement concrete in form of beams, cubes and cylinders were casted and tested regularly at equal interval of time.

3) All the r.c.c. samples were brought under one roof and kept in different environmental condition to see the effect of corrosion and then further ICCP method was used to control the effects of corrosion which could lead to failure of structure.

4) This study was considered in three parts , firstly we tested three different beams of similar shape and size with different reinforcement further we used cubes and cylinders individually and lastly we tried using them in pairs to form circuits to evaluate their performance in circuit as in a big structure..

2.3 Methodology of the study

Methodology of this study can be divided as following:

1) Experimental Arrangements
All the beams, cubes and cylindrical moulds and resistivity meters to be required during the course of study were arranged. Casting of different samples with use of reinforcement and cover blocks was done; continuous watch was kept using resistivity meter on impact of corrosion on samples.

2) Specimen Preparation of beam , cube and cylinders
The concrete specimens were prepared in Material Testing laboratory of Civil Engineering Department in Delhi Technological University. The prepared samples consist of concrete cubes of 150mm size ,beams of size 675 mm x 150mm x 150mm and cylinders of size 75 mm dia x125 mm height.

3) Allocation of specimens
The various cubes, beams and cylinders with various types of reinforcement were given wet and dry cycles to see the accelerated effect of corrosion.

4) Testing of Specimen
After casting different small structural members these members are checked daily to find changes observable in resistivity while samples are kept in normal environment and afterwords when samples are kept in corrosion active environment.

5) Data collection
The details of resistivity measured at equal interval of time on different samples were collected and recorded weekly to check the change in probability of corrosion. The data collected daily was recorded in tabular form to check the change in resistivity and it can be seen in table 6, 7, 8 and 10 .

6) Compilation of Result

The various samples tested individually and in groups using direct current supply were now considered together to study the effect of cathodic protection on different samples having different shape, size and reinforcement . The data collected and noted in tables was studied to check the change in resistivities of one sample with other and changes observed after wet and dry cycle .

CHAPTER-3:LITERATURE REVIEW

OVERVIEW

Cathodic protection (CP) is an electrochemical repair technique that is been used for the repair of reinforced concrete structures worldwide. Cathodic protection generally works by the passing of a small electrical current from the anode to the corroding steel reinforcement thereby protecting it from further deterioration by increasing the hydroxyl ions locally. Cathodic protection has mainly been incorporated with repair work of concrete as a means of rehabilitating deteriorated highway concrete structures with varying levels of chloride contamination, corrosion and spalling. However, we have also implemented the use of cathodic protection on small structural members like beams, cubes, cylinders and by pairing them in different order to check the effect of cathodic protection in different order of arrangement of the structural members. The two principal types of cathodic protection systems commonly used are the impressed current cathodic protection (ICCP) and the sacrificial anode cathodic protection (SACP).We have used impressed current cathodic protection for analyzing the effect of cathodic protection on beams, cubes and cylinders as it is a more reliable method for protection of reinforced concrete from the effect of corrosion due to following reasons:

1. Impressed current cathodic protection is having a very good monitoring system which enables to provide continuous watch on functioning of power supply for complete protection of structure from corrosion.
2. This method is more certain in defining the time and age of protection for the structure .Where as sacrificial anode system cannot assure the life span of element used as anode, due to which it becomes very uncertain.

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Cathodic protection systems protect a wide range of metallic structures in various environments. Common applications are: steel water or fuel pipelines and storage tanks such as home water heaters; steel piers piles; ship and boat hulls; offshore oil platforms and onshore oil well casings; and metal reinforcement bars in concrete buildings and structures. Another common application is in galvanized steel, in which a sacrificial coating of zinc on steel parts protects them from rust.

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Cathodic protection is a method to control the corrosion of steel in contaminated concrete that works by making the embedded reinforcement steel cathodic**.** When the steel becomes cathodic, hydroxyl ions are accumulated around it making it passive for longer time. The reinforcing steel is electrically connected to another metal that becomes the anode with or without the application of an external power supply. The cathodic protection systems that work in the absence of an external power supply and in the presence of a less noble metal (like zinc) to act as anode are referred to as sacrificial passive systems. In case of an impressed current cathodic protection, an external power supply is used to force a small amount of electric current through the reinforcing steel to counteract the flow of current caused by the corrosion process. A metal, like platinum, serves as anode which corrodes at a very slow rate.

G.K Glass and J.R Chadwick [5] investigated limitations of cathodic protection and suggested that cathodic protection can be used to protect almost any type of reinforced concrete structure, including horizontal slabs, walls, towers, beams, columns and foundations**.** However, this method has the following limitations:

1. Cathodic protection cannot not replace corroded steel; it can protect the corroded reinforcement from further action of corrosion till it is supplied with direct current.

2. Impressed current cathodic protection systems are not recommended for general usage on prestressed concrete structures because hydrogen produced can make the high-strength steels brittle in nature.

3. Passive sacrificial systems can be used for post- tensioned structures after detailed corrosion analysis[5].

4. Electrical continuity of the reinforcing steel and ionic conductivity of concrete must be confirmed during system installation[21,15] .

Negative effects induced by CATHODIC PROTECTION

Pedeferri[40] investigated on cathodic protection on new concrete constructions and suggested negative effects induced by cathodic protection which can affect the concrete, its adhesion to rebars and their hydrogen embrittelment.

Schuten g et al.[38] investigated on increase of alkalinity causing concrete degradation and suggested that the increase of alkalinity around the reinforcement can cause damage if the concrete contains alkali-reactive aggregates. In short run experiments change of the solution composition near to the steel cathode promoting expansive alkali-silica reaction (ASR) in concrete containing potentially reactive siliceous aggregates are normally found only for current densities higher than those normally used for cathodic protection. In long term run experiments the situation could be different, at least in the case in which relatively high current densities (> 10 mA m-2 of concrete surface) are reached. Consequently, if the structure to be protected contains aggregates which may be sensitive to alkali the risk of ASR has to be considered and made negligible by controlling the current density.

Mietz et al.[36] Investigated about behavior steel reinforced concrete structures under the action of cathodic protection ,where they explained about adhesion losses generated in reinforced concrete. At very negative potentials (i.e. at high current densities), loss of adhesion between rebar and concrete can occur. Many uncertainties remain about the phenomenon but for long term polarization (like in the case of CP) -1.1 V is usually indicated as the lower limiting potential and in any case this problem is mainly associated with non-ribbed bars[43,7].

Hydrogen embrittelement

B.S Wyatt[4] and Grefstad k [29] examined adverse effects of cathodic protection and explained the most important side effect of cathodic protection that is the embrittlement of steel caused by atomic hydrogen. Some types of high strength steels utilized in prestressed constructions can be subjected to hydrogen embrittlement if their potential is brought to values at which hydrogen evolution can take place. Part of the developed hydrogen can enter these steels and make this phenomenon possible. In alkaline environments (pH >12) and thus on cathodically protected reinforcement[3],. For these reasons, even in the most critical conditions (steel more susceptible to the embrittlement, such as quenched and tempered, critical deformation rates, presence of sharp defects). Low strength ferritic steel utilized for reinforced concrete constructions is not susceptible to hydrogen embrittlement. High strength steels utilized for prestressed constructions have to be considered susceptible unless contrary evidence is given. This type of susceptibility depends on many metallurgical and electrochemical variables and thus varies with factors such as (composition, heat and mechanical treatments, presence of notches or defects due to corrosion, value of load and its variations giving low strain rate, environmental conditions, etc)[12,10,4].

Impressed current cathodic protection (ICCP)

Christodoulou C et al. [34] Assessed impressed current cathodic protection its benefits over other method of cathodic protection, the majority of cathodic protection systems applied to reinforced concrete structures internationally, are impressed current cathodic protection (ICCP) systems. ICCP systems arrest steel reinforcement corrosion activity by supplying electrical current from an external source to overcome the ongoing corrosion current in the structure. ICCP involves the permanent installation of a low voltage, controlled electrical system which passes direct current to the steel so that all of the steel is made into a cathode, thus preventing the steel from corroding. The anode can be applied on the surface of or drilled into small holes in the structure. It is the main electrochemical treatment that provides protection that can be effectively monitored and controlled in the long term. The main components of a typical ICCP system include the anode system, reinforcing steel, electrolyte (in the concrete), cabling, monitoring devices, e.g. reference electrodes and a direct current (dc) power supply. Protection is provided by connecting the impressed current anode to the positive terminal and the reinforcing steel to the negative terminal of a dc power supply. The direct current is normally provided by an ac powered transformer rectified or equivalent power supply. Typical dc power supply outputs are in the region of 1–5 A and 2–24 V to each independently controlled anode zone[34,31,15]. The main benefit of ICCP is its flexibility and durability. The current output of the power supply can be adjusted to optimize the protection delivered. ICCP systems can be controlled to accommodate variations in exposure conditions and future chloride contamination. The durability of ICCP systems is largely determined by the choice of anode. This is because the damaging reactions are moved from the steel to the installed anode. There are a number of impressed current anode systems for reinforced concrete on the market. These include conductive coatings, titanium based mesh in cementitious overlay, conductive overlay incorporating carbon fibres, flame-sprayed zinc and various discrete anode systems. There are a range of factors which influence the selection of impressed current anodes for ICCP systems for particular applications[12]. These include environmental conditions, anode zoning, accessibility, maintenance requirements, performance requirements and operating characteristics, life expectancy, weight restrictions, track record and costs.

J.P. Broomfield and J.S. tinnea [6]investigated on functioning of impressed current cathodic protection system in detail and suggested impressed current cathodic protection systems can work very well and provide a cost effective alternative to galvanic anodes in certain situations. keeping the following guidelines when considering a retrofit project.

1) Ensure that the platform is a viable candidate for ICCP, that the current requirement and water depth are applicable, and that the structure has available power and sufficient remaining life requirements to justify such a system.

2) Pre-qualify your system choice, get performance data, and check other client references. Many impressed current cathodic protection systems are poorly designed and will fail early, so ask the designers for a written warranty.

3) If structure has galvanic anodes, try to schedule the retrofit to make use of the remaining current capacity[27].

4) If applicable, prepare a galvanic retrofit design and get installed price for comparison. If the installed cost of the ICCP system isn't significantly less, then go with the galvanic system.

Christodoulou C et al.[34] and J.P. Broomfield [12] explained the advantages of impressed current cathodic protection. ICCP systems allows significant cost savings ,that is possible due to minimal concrete removal (limited physical repair) as ICCP requires that only physically unsound concrete i.e. delaminated, honeycombed, cracked concrete be removed while chloride-contaminated but sound concrete is left in place. As a result, ICCP retains more of the original structure with less effect on aesthetics. Consequently, the installation of ICCP systems eliminates the need for removing chloride-contaminated but sound concrete with associated reduction of noise, dust, disruption and propping. Installation of ICCP also limits the need to cut behind the reinforcement[5]. ICCP controls corrosion at any chloride level regardless of present or future chloride levels or carbonation. It controls pitting and general corrosion and prevents accelerated corrosion around repairs. Pedeferri [40] suggested that ICCP can be applied to specific elements, e.g. crossheads or to entire structures and can be used to protect any buried or submerged metallic items. The trials showed that CP stopped corrosion and confirmed it as a cost effective solution to deal with the chloride affected reinforced concrete structures. As a result, ICCP has been adopted as the major rehabilitation method to stop corrosion on the Midland Links structures [24], with more than 100,000 square meter of concrete being protected using this technique. The high confidence gained in CP has lead to its wide application elsewhere in the world on reinforced concrete structures including bridges (bridge decks and substructures), car parks, tunnels, ports and harbour facilities (jetties/wharves), industrial and residential buildings and marine structures [4].

As a consequence of the experience gained from Christodoulou C et al. [34], good specifications and standards have been developed over time and are now available to assist with the design, installation and performance monitoring of ICCP systems, which can be designed with up to 30 years design life subject to the quality of the existing concrete. However, an impressed current CP system could in theory have a life expectancy of between 10 and 120 years depending on the type of anode system selected and the monitoring and maintenance regimes put in place. Any electrical components and cabling would be expected to be renewed after about 20 years but with proper design, monitoring and maintenance, the period to first maintenance can be well in excess of this time frame[12,5,40].

Impressed current CP systems can be divided into zones to account for different levels of reinforcement, different environments or different elements of the structure. It can also be utilized to provide protection to critical reinforcement at great depths i.e. along the length of half-joints and deep bearing shelves. With ICCP systems, various remote monitoring and control options are available to enable selective and continuous monitoring to be undertaken for each anode zone[2].

R.Podler et al.[21] and Bertolini et al [27] explained the disadvantages of impressed current cathodic protection and brought all concerning points related with it. They elaborated that application of ICCP mandates the structures owner to undertake regular monitoring in order to assess the levels of cathodic protection being afforded to the structure. Therefore, an ongoing cost of electrical power (usually insignificant) and cost of specialist monitoring, control and assessment. Competent, highly trained & specialized persons are required in order to monitor ICCP system performance for the service life of ICCP systems. There is an initial high cost outlay to install ICCP systems and future regular maintenance/controlling costs are approximately Rs 25,00,000/annum [27] to ensure effectiveness of system. ICCP requires a constant electrical power (permanent power) supply and where none is locally available arrangements must be made and allowed for in the costing. In the case of the impressed current CP systems utilizing discrete anodes extensive drilling is required as part of the installation process. The drilled holes and chases have an impact on the appearance of the structure and there is also concern about Health and Safety issues due to the risk of vibration white finger through the use of extensive drilling[18]. Grefstad k [29]explained the installation problems associated with the use of certain impressed current anode systems such as discrete anodes in areas of congested steel and the application of discrete anodes to the soffits of structural elements. Also, discrete anodes occasionally have problems associated with achieving sufficient current distribution when compared with surface applied impressed current anode systems The interface between cementitious overlay and bearing shelves in the case of impressed current anode system acts a potential point of weakness as ponding/excess seepage can potentially cause freeze/thaw action. ICCP system power supplies, monitoring systems and their enclosures are often vulnerable to environmental damage, in particular vandalism and to atmospheric corrosion. Cabling and control boxes associated with ICCP systems are required to be strategically placed in order to avoid the risk vandalism[42]. Certain impressed current anode systems such as conductive coating anode systems cannot tolerate water during installation or prolonged wetting during operation. They also do not tolerate traffic or abrasion. Bulky equipment is required for the installation of certain impressed current anode systems, e.g. the Thermally Sprayed Zinc anode system. The cementitious overlay for mesh and overlay anode system changes the profile, loading, appearance and clearances of a structure[2]. Clearance may be an issue, e.g. on the soffit of over bridges, around bridge bearings or in car parks[11]. When an 'as shot' appearance is unacceptable then a flash coat would need to be applied in order to achieve the desired finish. Due to the risk of hydrogen evolution and possible occurrence of hydrogen embrittlement on high strength steels ICCP is not routinely applied to any prestressing or post-tensioned elements without specific consideration for suitable safeguard criteria[4,29]. Provided the tendons are in good condition with no corrosion then the use of ICCP is usually considered with suitable safeguard criteria involving the minimization of overprotection and the use of appropriately placed monitoring probes at carefully selected locations, together with appropriately screened cables. The use of impressed current CP systems in the presence of Network Rail lines and equipment or other electrical systems needs to be strictly controlled in order to prevent incidents of stray current interfering with associated overhead line/equipment and track signaling equipment[38]. In addition, any isolated reinforcement steel or adjacent surface mounted steelwork must be made continuous with the ICCP system in order to prevent stray current corrosion.

Having discussed the most important attributes of a reliable system, let us now investigate some of the more commonly used system designs to see where they succeed and where they may fail. The examples given below are taken from the research papers of Schuten g et al.[38]and J.P. broomfiled[12].

Suspended Anodes - In this type of system, anodes are often weighted and contained within a dielectric frame, then freely suspended from above water locations, either from the feed cable or a strain member. This can be a viable approach for shallow water structures with a relatively short life expectancy (< 5 years) and a moderate to high current demand. Anode failure will occur on a regular basis, but with a very low replacement cost, the systems can be replaced easily and therefore still represent a decent short-term option. This is not a good solution for deeper water structures. Care must be exercised when deciding the location the anodes to ensure that boats or sport fishermen cannot contact the live suspended wires. Silicon Iron or Graphite anodes can work well in this application[38].

Gravity Sleds - In this type of system, anode sleds are designed to sit on the sea floor at some distance from the structure, connected by a seabed cable. Some are designed to become silted while others are much larger, designed to keep the anodes in seawater. In either case gravity sleds can be a good design[21]. In our experience most failures of these systems have resulted from damage to the seabed cable or failure of the anode-to-cable connection. However, if these design issues are properly addressed, a gravity sled can be very reliable. Most remote systems may need some galvanic anodes to assist in shielded area polarization.

Buoyant Sleds - These systems are very similar to gravity sleds, except the anode elements are held up in the seawater by means of buoys, normally integral with the anode . A variation on this design is shown below. The advantage of the buoyant sled is that the critical elements can move freely if hit by falling debris, and the overall structure is much lighter. These systems have generally enjoyed good long term success.

Bertolini et al.[38] explained close fitted anode system - In this system, anodes are attached directly to the structure and require dielectric shields. This system does not lend itself to retrofit on platforms due to the excessive amount of pre-installation cleaning required and the complexity of the cable installations. Cantilevered versions of the same design concept are available but have the same basic problem. These systems work well for docks and inshore facilities.

Schuten g et al.[38] Elaborated in detail the tensioned string anodes system-and explained its working that this system uses a tensioned string of anodes , usually mixed metal oxide, although early versions used platinized niobium. Tensioned systems have had mixed results: failures are typically caused by wave action and abrasion with subsea members. As the strings get longer in deeper water, more tension is required to minimize deflection of the string subsea or alternatively a number of mid-string tie backs are required to limit movement. Earlier systems had tensioning equipment above the water line, this made the section of anode string through and above the splash zone very susceptible to damage from storms, and system life was often shorter than anticipated. Later projects moved the tension point to a sub-sea location, and used a pull tube to get the cables through the splash zone. This version is expected to perform much more reliably.

Hybrid Systems were also investigated and explained by Schuten g et al.[38], in hybrid system we use a combination of impressed current cathodic protection and galvanic anodes often will provide a solution with the best of both worlds. The ICCP provides large packages of current usually 80 - 90% of the total demand. Strategically located galvanic anodes assist in current distribution to the "hard to polarize" areas. One of the more amusing myths about cathodic protection is the "line of sight" protection theory. While this obviously is not valid, complex geometry shielding is a reality. This is more a function of current requirement than any line of sight effects; however hybrid systems can successfully address these areas. For this reason, installation of an impressed current retrofit on a platform originally protected by galvanic anodes will work very well if the project is timed such that some original galvanic material remains.

Sacrificial anode cathodic protection (SACP)

A sacrificial anode is a form of cathodic protection, it is made from a metal alloy from the galvanic series which has a more negative electrochemical potential than the steel reinforcement of the structure. This works because the difference in potential between the anode and steel causes a positive current to flow in the electrolyte, making the steel more negatively charged, thus becoming the cathode.

In the application of passive cathodic protection, a galvanic anode, a piece of a more electrochemically "active" metal, is attached to the vulnerable metal surface where it is exposed to an electrolyte. Galvanic anodes are selected because they have a more "active" voltage (more negative electrode potential) than the metal of the target structure. R.Podler et al.[21]explained that the galvanic anode continues to corrode, consuming the anode material until eventually it must be replaced. Polarization of the target structure is caused by the electron flow from the anode to the cathode, so the two metals must have a good electrically conductive contact. The driving force for the cathodic protection current is the difference in electrode potential between the anode and the cathode.

Galvanic or sacrificial anodes are made in various shapes and sizes using alloys of zinc, magnesium and aluminum. ASTM International publishes standards on the composition and manufacturing of galvanic anodes. In order for galvanic cathodic protection to work, the anode must possess a lower (that is, more negative) electrode potential than that of the cathode (the target structure to be protected). The table no 1 below shows[21] a simplified galvanic series which is used to select the anode metal. The anode must be chosen from a material that is lower on the list than the material to be protected.

TABLE 1 . Galvianic series [21]

Metal	**Potential with respect to a Cu:$CuSO_4$ reference electrode in neutral pH environment (volts)**
Carbon, Graphite, Coke	+0.3
Platinum	0 to -0.1
Mill scale on Steel	-0.2
High Silicon Cast Iron	-0.2
Copper, brass, bronze	-0.2
Mild steel in concrete	-0.2
Lead	-0.5
Cast iron (not graphitized)	-0.5
Mild steel (rusted)	-0.2 to -0.5
Mild steel (clean)	-0.5 to -0.8
Commercially pure aluminum	-0.8
Aluminum alloy (5% zinc)	-1.05
Zinc	-1.1
Magnesium Alloy (6% Al, 3% Zn, 0.15% Mn)	-1.6
Commercially Pure Magnesium	-1.75

Berotolini et al.[39] investigated sacrificial passive cathodic protection systems and subdivided them in following methods

a) Zinc sheet anodes, precoated with a conductive hydro gel adhesive, are applied to the surface of the concrete. The formed anode is called zinc hydro gel anode and its appearance is improved by coating with various paints.

b) Zinc or zinc alloys are sprayed to the concrete using arc spray or flame spray equipment.

c) Embedded galvanic anodes are embedded within the repair concrete connected with the reinforcing steel. The anodes are installed along the perimeter of concrete patch repairs to protect adjacent areas from corrosion due to the anodic-ring effect.

Christodoulou C et al.[34]and J.P. Broomfield[12] Investigated on impressed current cathodic protection and subdivided various types of ICCP systems on basis of anode installation, which are as following:

a) Surface-mounted anodes without overlays are mounted on the surface of the concrete and do not require a cementitious overlay[34]. However, the wear resistance of the system is reduced.

b) Conductive mastic anodes consist of anodes embedded on the surface of concrete having a conductive coating. They are used on vertical surfaces, ceilings, and columns.

c) Plate-type anodes consist of manufactured anode plates glued to the concrete surface.

d) Surface-mounted anodes with overlays are generally used on horizontal surfaces and require a cementitious overlay of 13 mm minimum thickness[12].

e) A mesh of a noble metal anode is fixed to concrete with multiple pins, called mesh-type noble metal anodes, which are covered with a cementitious material.

f) Conductive polymer concrete strips consist of a series of conductive polymer concrete strips containing a noble metal anode that is fixed to the concrete surface and covered with a cementitious overlay[7].

g) Embedded anodes system is embedded in the surface of the concrete or is placed at the level of the reinforcement in new construction.

h) Saw slot anodes are made by creating a series of small depth and width saw slots in the concrete surface which are filled with a noble metal anode and a conductive polymer concrete.

i) Anodes can be placed at the level of the reinforcement during new construction. This anode must not have direct contact with the reinforcing steel.

Schuten G et al.[38] investigated on advantages of sacrificial anode cathodic protection and explored below mentioned points. Unlike ICCP, an external power source is not required to install SACP. This greatly reduces the start up costs as no provision has to be made to connect to a power supply. Also, the SACP system is easier to maintain and this leads to significantly less minimal running costs throughout the life of the system. In addition, the SACP system voltages and current outputs are lower compared to the ICCP system, leading to a low risk of cathodic interference in adjacent structures. Consequently, the imposed potential is unlikely to exceed the _900 mv defined in BS EN 12696:2000 as being capable of inducing hydrogen embrittlement of steel reinforcement[34].

Sacrificial anodes are relatively easy to install as sound but chloride contaminated or carbonated concrete does not require replacement, only specific areas require concrete breakout. Repairs can be targeted; focusing on specific areas of deterioration or elements of the structure, preventing inefficient protection of the steel and therefore keeping costs down[7]. The anode also controls corrosion in areas adjacent to concrete repairs that would normally require removal if only conventional concrete patch repair was carried out. Since concrete breakout is minimized, it is unlikely that temporary works such as structural propping, which is expensive, will be required during repair. Also with minimal breakouts, uncertainties over structural behavior due to redistribution of stresses are reduced. These all leads to less traffic disruption as the remedial works can be completed in a shorter timeframe. A SACP system is easier to design and specify as it has fewer critical components, with the main critical component being the anode itself. The system is considered to be a sustainable option as it is making the most of the structure in its current form and extending its life through relatively minor repair work. There is also less waste going to landfill as often relatively little concrete is broken out and repaired[39]. There is also an issue of ongoing liabilities; many Highways Agency (HA) structures are maintained as part of a Managing Agent Contract (MAC) which is run by a contractor for a period of time, this means that a structure could be maintained by several different managing agents throughout the SACP system's life. The handover of an SACP system is much less involved, requiring no document handover, data exchange or knowledge transfer. Overall the SACP system is much cheaper than the ICCP system, in the short and medium term, is easier to install, no monitoring is required and it causes less disruption as less time is required on site[42].

Strong GE et al.[42] and Schuten G et al.[38] described disadvantages of sacrificial anode cathodic protection. The main disadvantage is the uncertain lifespan of the anodes; the life expectancy of the system is dependent upon the average current output of the anodes. The anodes only have a finite amount of material available for sacrifice and a higher current uses up that material at a higher rate. Changing conditions can affect the current output of the anode. Factors which are known to affect the current output are chloride content, temperature, oxygen content and humidity. There is no way of knowing when all of the material in the anodes have been used up and the anode has stopped working, this is a predicament, as new deterioration is likely to be the first sign that the anodes are spent which is also one of the main disadvantages[12].

Compared to ICCP, the current output of the SACP system is limited and this means that the current output cannot be altered over time to compensate for changing conditions. There is no way of adjusting the SACP system other than adding or taking away anodes and because the system is not monitored in the same way as ICCP, it is difficult to know when adjustments are required; this may lead to a failure to arrest active corrosion[38]. Monitoring of an SACP system takes the form of survey at set intervals to monitor for signs of deterioration. Although there are no running costs associated with the system itself, the structure requires a regular visual and delimitation survey to monitor its condition; however, this can be done during the structures regular inspection schedule. As a design consideration, the resistivity of the concrete must be taken into account as the lower driving voltage of the anodes means they may not work in high resistivity environments.

D.D. McDonald and M.C.H. Mckubre [14] investigated cathodic protection for partly buried and marine structure where they suggested that the corrosion process in buried or partly buried structures is due to current flow from anode to cathode through the ground by ionic conductivity and from Cathode to anode through the metal by electric conductivity. At the anode the metal oxidation occurs, whilst at the cathode hydrogen or oxygen reduction occurs. Anodic and cathodic areas can be closer and move along the structure surface, producing uniform corrosion, or an area can become permanently anodic, producing localized corrosion. Podler RB [35]. Explained the factors affecting the corrosion in the ground, most of them ascribable to the physical–chemical properties of the soil, such as: (1) conductivity, (2) aeration and permeability, (3) acidity, (4) humidity (water content), (5) presence of sulfates and chlorides, (6) presence of biological species and (7) presence of stray currents. The first four above-mentioned factors are strictly correlated. During the electrochemical corrosion process, several anodic (oxidation) and cathodic (reduction) reactions occur. The principle anodic reaction in the corrosion of an offshore structure is as shown below in figure 2.

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

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- . \quad (2)$$

TABLE 2.Principle anodic reaction

CP system characteristics

Criterion	Galvanic	ICCP
External power	No	Yes
Driving voltage	Fixed	Variable
Current required	Limited and low	Variable and high
Soil conductivity	High	Wide range
Interference	Negligible	Possible and risky

CHLORIDE ACTION

Chloride attack poses a significant threat to reinforced concrete especially for structures in marine environments or those that are likely to be exposed to high concentrations of salts. The net result of chloride attack is the corrosion of steel reinforcement, leading to cracking and spalling of concrete.

F.J. Presuel et al.[7] Investigated the effects of cathodic protection and chloride action in which they told the mode of attack relies on salts and other corrosive substances, carried by moisture, being absorbed into the concrete via its pores and micropores through capillary action. Once absorbed, these substances act to reduce the PH value of the concrete thereby eliminating its passive oxide layer which would otherwise provide protection to the steel reinforcement. Corrosion takes place as the chloride ions meet with the steel and the surrounding passive material to produce a chemical process which forms hydrochloric acid [29]. The hydrochloric acid eats away at the steel reinforcement.

R.E Stratful [9] Elaborated and discussed factors that contribute to the rate at which concrete deterioration can occur as a result of chloride attack. The physical characteristics of the concrete itself are chief among these variables. By its very nature, concrete is a porous material with the degree of its strength and durability determined by factors such as the water/cement ratio, compaction and curing. Given the action of chloride attack, the density of concrete becomes an important influencing factor on the rate of its deterioration: concrete with smaller pores and lower pore connectivity will absorb less water or vapour and inhibit its transport thus slowing down the ingress of chlorides into the structure[4]. The physical condition of surface concrete plays an important role in the rate of deterioration. Where there is existing surface damage particularly in the form of abrasions, cavities or other impact damage the resultant cracks serve to speed up the transportation of moisture and ions to the steel which amplifies the rate of corrosion. Freeze thaw cycles can then exacerbate the process further[10].

By their very nature and location, sea walls and other marine structures remain most susceptible to chloride attack as sea water is a major source of chloride ions[33]. Chemical manufacturing and processing plants, road bridges, car parks and underground structures are also at risk of premature failure especially where de-icing salts have been used and remain in situ.

CORROSION MEASURING INSTRUMENT

Resistivity meter allows us to measure the resistivity of concrete and reinforced concrete which can directly be related with effect of corrosion on structure. Thus it can be said as, measurement of concrete properties, such as resistivity and potential of concrete can assess the probability of corrosion of reinforcing steel.

C.Andrade and C.Alonso [16] and G.K Glass et al. [19] investigated on test methods for corrosion rate measurement and suggested, corrosion of steel in concrete is an electro-chemical process that generates a flow of current. Resistivity of the concrete influences the flow of this current. The lower the electric resistance, the more easily corrosion current flow through the concrete and the greater is the probability of corrosion. Thus, the resistivity of concrete is a good indication of probability of corrosion. Resistivity Meter can measure the electrical resistance of reinforced concrete components. The probable rate of corrosion with respect to value of resistivity of concrete is normally considered as given in table 3 below

TABLE 2a.Resistivity level to parametrise corrosion.

Resistively level (Kilo-ohm / cm)	**Possible corrosion rate**
< 5	Very high
5 to 10	High
10 to 20	Moderate to low
> 20	Insignificant

Resistivity meter is very handy and portable equipment weighing about 2.2 Kg. It has two or more probes, which are placed on concrete surface with conductive gel between probes and surface. The concrete resistivity is displayed on a LCD. Now a days, resistivity meters are available with non-volatile memory and colored graphic display from which data can be transferred on PC. To measure the resistivity, metallic probes are placed over the concrete surface [18]. A known current is passed on the outer probes and resulting potential drop between inner probes is measured. The resistance is computed by dividing potential drop by the current. A conductive gel is used between probe and concrete surface to make effective contact.

R.Polder et al.[15] explained about corrosion analyzing equipment ,these equipments work on basis of difference in potential between concrete surface and steel is a good indicator of current flow. The electrochemical process produces an electric current, which is measurable as an electric field on the surface of the concrete. This potential field can be measured with an electrode known as Half-cell. By making measurement over the whole surface, a distinction can be made between likely corroding and non-corroding locations. The probability of corrosion with respect to the values of potential difference is normally considered as given in table below:

TABLE 3.Pottential value to parametrise corrosion rate.

Potential Value	**Possible Corrosion Rate**
</= 0.20 V	90% probability of no corrosion
0.20 to -0.35 V	Corrosion activity uncertain
> 0.35 V	more than 90%probability of corrosion

Corrosion AnalysingInstrument is small, handyequipment weighing about5.5 Kg. with large disp lay and simple operation. Measured values can be represented on the display. Measurements can be stored in the memory. Its data can be transferred to PC [15].

G.K Glass et al.[19] explained the procedure for application of corrosion measuring instrument on existing bridges**,** re-bars /pre-stressing wires are to be exposed to make electrical connections. For this, bore are to be made by drilling the concrete at desired locations and an electric cable is connected with pre-stressed cable and projected outside. After connecting them from outside, the same can be plugged back using epoxy mortar. The positive terminal of voltmeter is connected to exposed re-bars and negative terminal (common) to reference half-cell. The surface of concrete is divided in to number of grids. The reference electrode is moved along the nodal point and corresponding potentials are recorded. These are referred as corrosion potential.

RESIPOD RESISTIVITY METER

Resipod is a fully integrated 4-point Wenner probe, designed to measure the electrical resistivity of concrete in a completely non-destructive test. It is the most accurate instrument available, extremely fast and stable and packaged in a robust, waterproof housing designed to operate in a demanding site environment. The Resipod is the successor of the classic CNS Farnell Resistivity Meter.

Surface resistivity measurement provides extremely useful information about the state of a concrete structure. Not only has it been proven to be directly linked to the likelihood of corrosion and the corrosion rate, recent studies have shown that there is a direct correlation between resistivity and chloride diffusion rate and even to determination of early compressive strength. This makes it one of the most versatile NDT methods for concrete.

CHAPTER 4 EXPERIMENTAL PROGRAM

Materials

Reinforced concrete cubes , beams and cylinders were casted using IS guidelines (IS: 10262-2009). Diffrent grade of reinforcement was used keeping concrete of nominal mix(M-20) and different beams and cubes were casted using fy 500 , fy 415 and corroded bars. Direct current supply was maintained by use of two 12 volts battery in series to provide cathodic protection .

Cement

Cement used in the experimental work is Ordinary Portland cement – 43 grade .
The specific gravity of the cement was 3.16 in accordance with IS:2720 PART-III.

Aggregates

Coarse aggregate and fine aggregate were procured from local market.
The following tests were carried out on aggregates:
- Sieve analysis for fine aggregate and fineness modulus
- Specific gravity and absorption capacity for fine aggregate

Sieve Analysis for Fine Aggregate and Fineness Modulus

Sieve analysis determines the particle size distribution of aggregates using a series of square or round meshes starting with the largest at top. It is used to determine the grading, fineness modulus.

Results

Fineness modulus (F.M) = Σ cumulative coarser (%)/100
F.M. = 293/100 =2.93

Specific gravity of fine aggregate

The specific gravity of a substance is defined as the ratio between the weight of the substance and that of the same volume of water. This definition assumes that the substance is solid throughout.
Specific gravity test of fine aggregates was done in accordance to IS-2386 part-3, and found as 2.67

Coarse aggregates

In a similar manner like the fine aggregate, laboratory tests were carried out to identify the physical properties of the coarse aggregate and the results of sieve analysis are shown below:

a) Specific gravity = 2.76
b) Fineness Modulus = 5.86
c) Water absorption = 0.498

Reinforcement

Steel of different yield strength was used for example fy 500 , fy 415 and corroded bars were also used for analysis of cathodic protection.

Structural member:

In view of corrosion, protection on R.C.C. structure different small and medium size structural member having different shapes , sizes and different reinforcement were casted , for example – we have used different grade of steel starting from fe 500 , fe 415 and even corroded bars which were extracted from old corroded structural beam members being used as lintels above door – windows in a residential building.

1. First of all we started by casting three different beams of same size, using same coarse aggregate, aggregate and cement but with different grade of reinforcement which is shown in figure 1a,1b and 1c below.

Beam 1: Size =27'' x 6''x 6''[680mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= fy 500

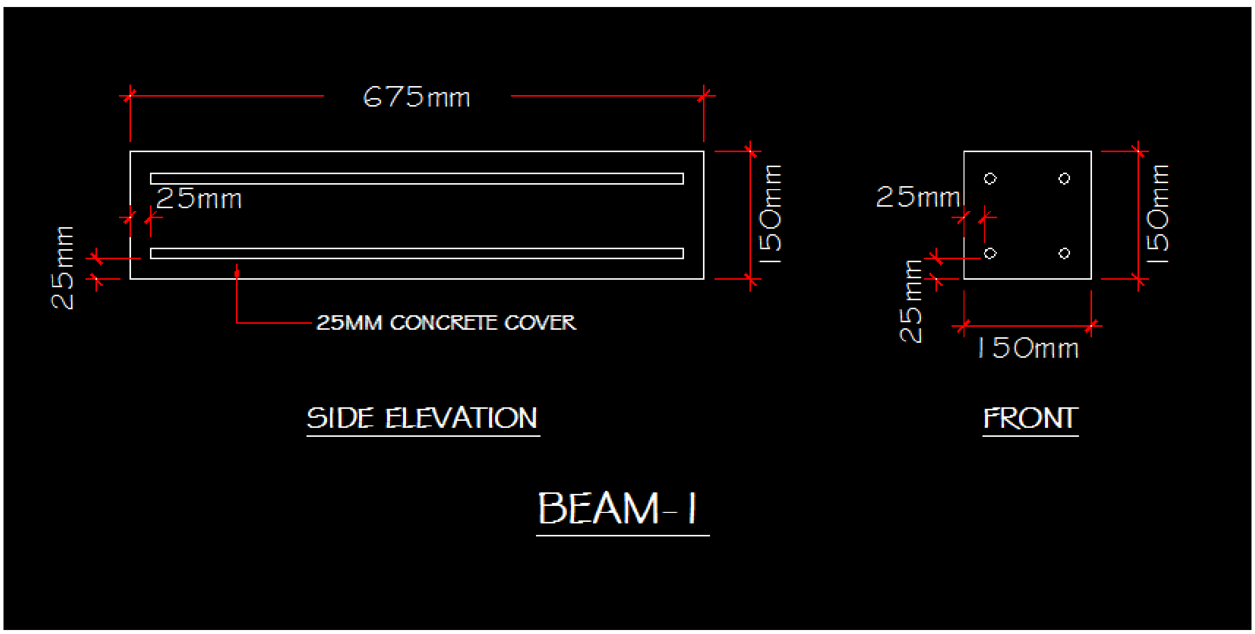


figure 1a. Section and elevation of beam1 .

Beam 2: Size =27'' x 6''x 6''[680mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= fy 415

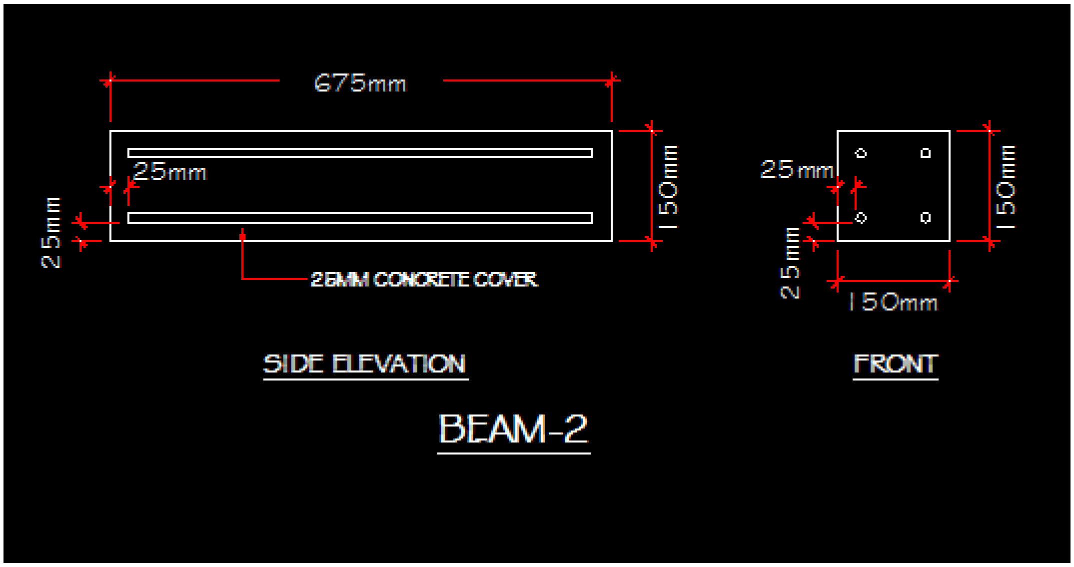


figure 1b. Section and elevation of beam2.

Beam 3: Size =27'' x 6''x 6''[680mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= corroded bars

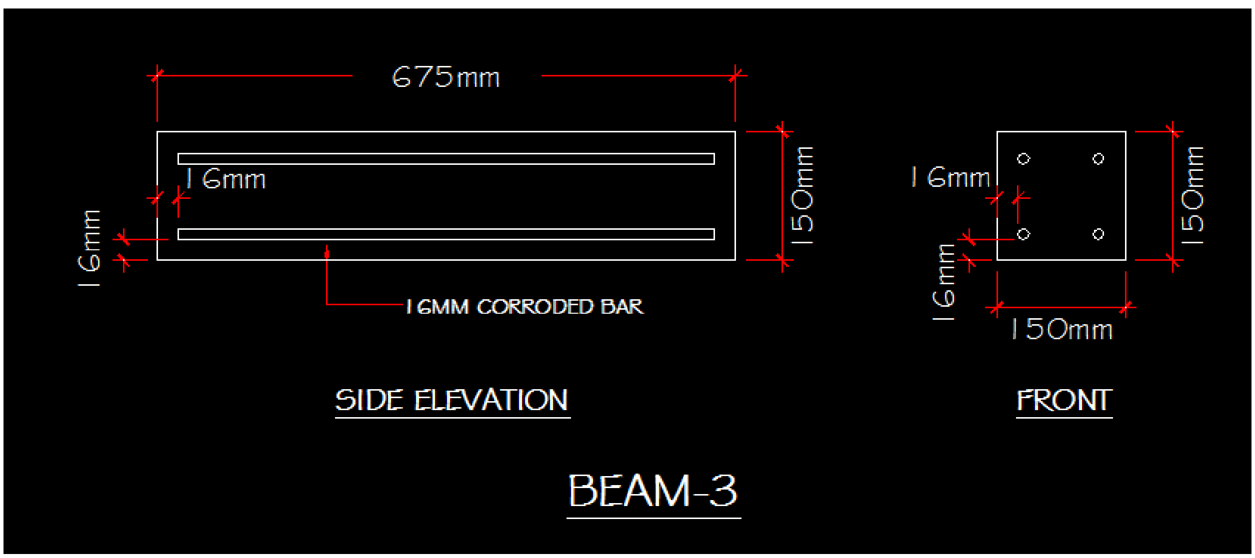


figure 1c. Section and elevation of beam3.

These beam structural members were cast in concrete laboratory using adequate cement concrete cover blocks below the reinforcement.The beam moulds were filled & given proper vibrations using table vibrator available in the laboratory, so as to provide adequate cover to reinforcement. These beams were later kept in corrosion active atmosphere as shown below in figure 2 and 3.

figure 2 .Placement of rings and main bars in beam.

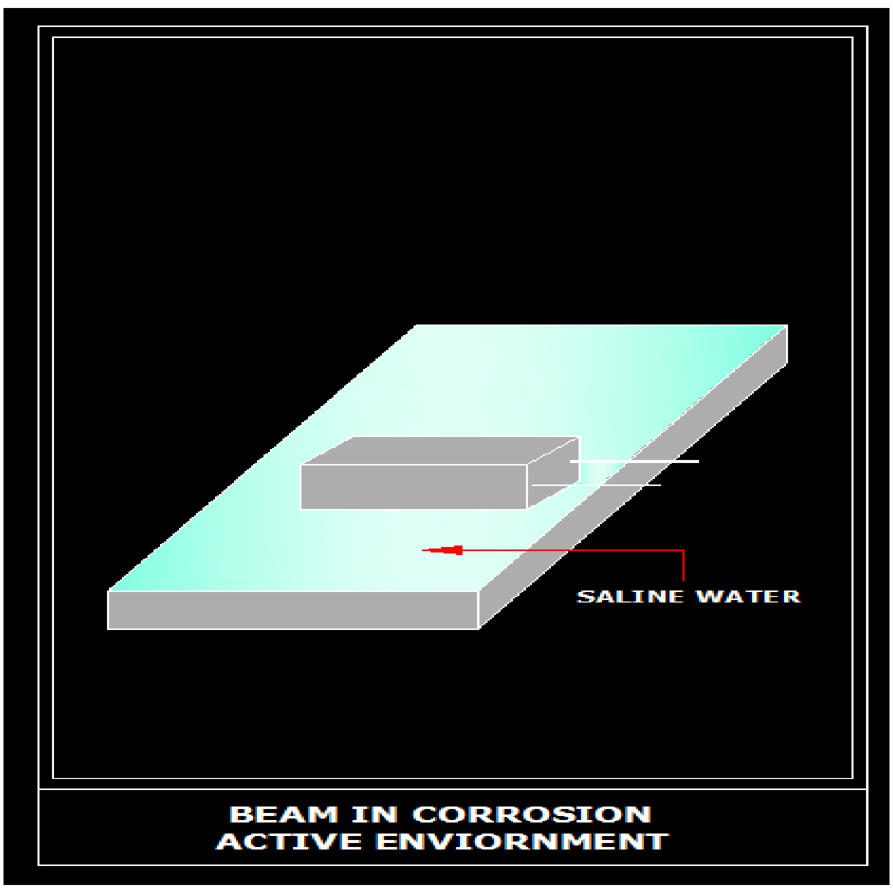
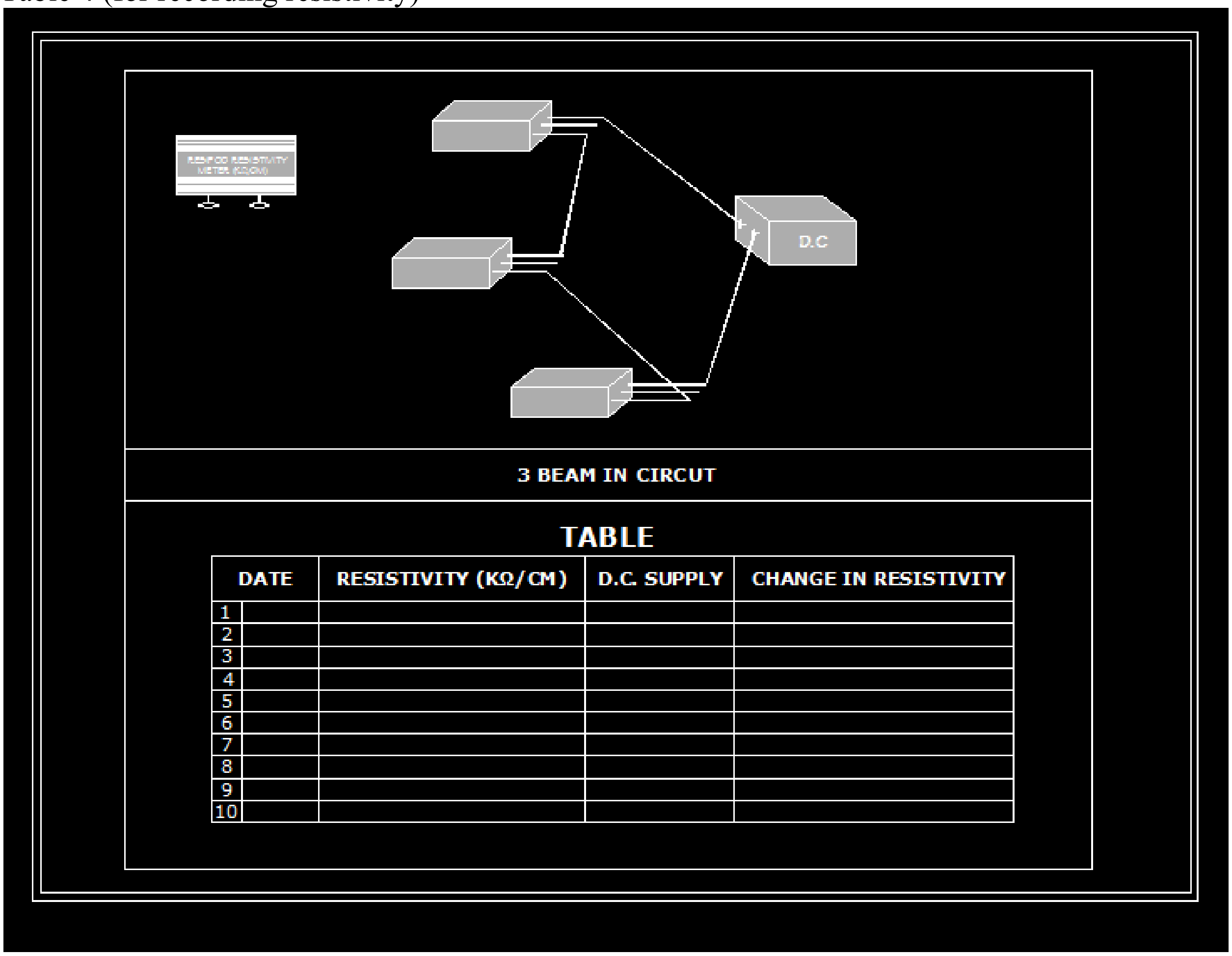


figure 3.beams placed in saline water.

The different beams were given same active atmosphere by sudden wetting and drying . Initially the beams were kept in water tub for curing . After 5 days of curing and 15 days of drying the samples were placed in saline water wherein the samples were daily inserted in saline water tub in morning then it was kept for drying in noon time and then again they were inserted in the tub with change of water and addition of adequate amount of salt after every 3 days .Salt concntration was kept 9-10 wt%. This way after continuous wetting and drying for 19 days we observed a drastic change in resistivity of structural member which is recorded in tabular form as shown below in table 4.

Table 4 (for recording resistivity)



DATE		RESISTIVITY (KΩ/CM)	D.C. SUPPLY	CHANGE IN RESISTIVITY
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

It can be understood from the table above that sudden change in resistivity is observable after few days of sudden wetting and drying, which leads the beam to be more prone to corrosion which can be understood by the table given ahead in result section.

2. After casting of beams , three cubes were cast with keeping the concrete mix M-20, but with different grade of reinforcement in one sample , one cube was provided with corroded bars where as other two cubes were provided with fy 500 as shown below in figure 4a and 4b.

Cube1: Size =6’’ x 6’’x 6’’[150mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= FY500

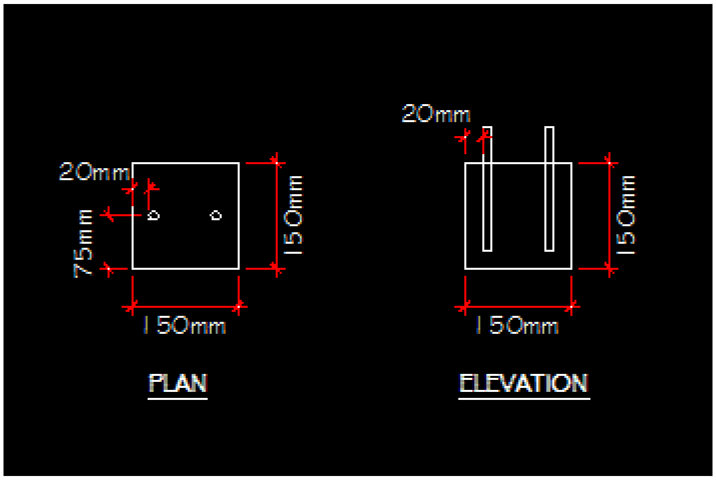


figure 4a. Section and elevation of cube 1.

Cube2: Size =6'' x 6''x 6''[150mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= Corroded bars

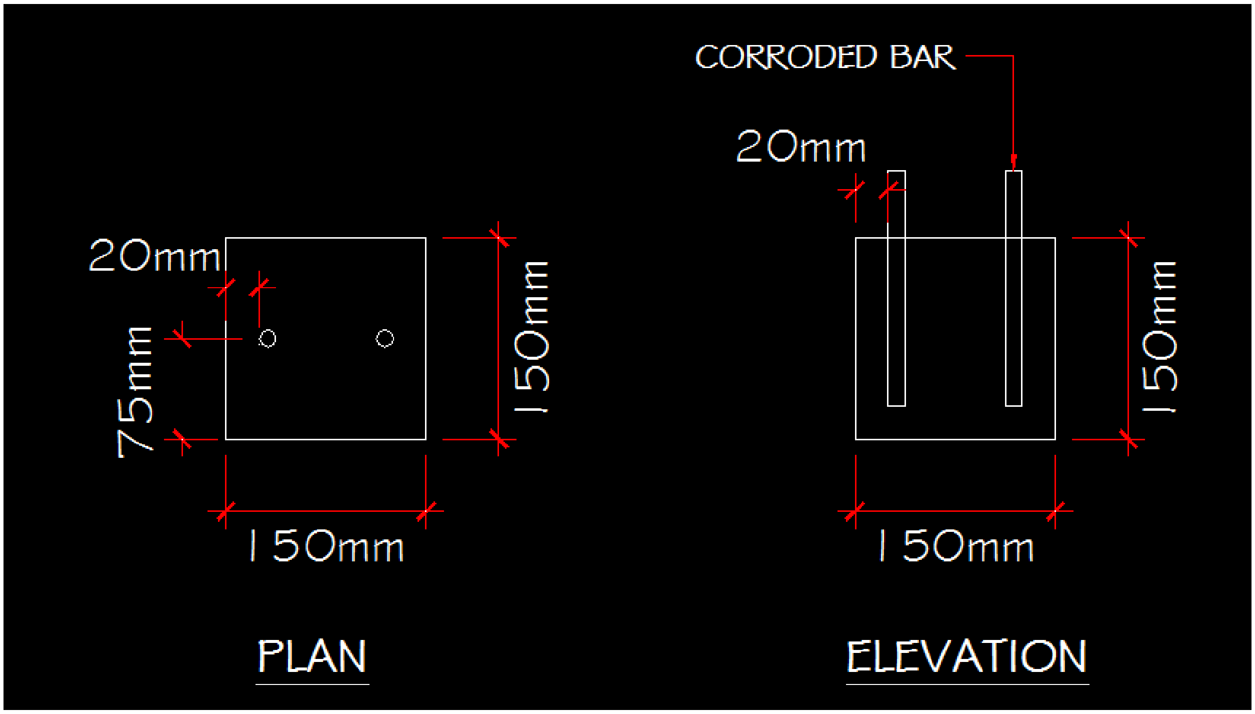


figure 4b. . Section and elevation of cube 2.

Cube3: Size =6'' x 6''x 6''[150mm x150mm x150mm]
Concrete = M-20 grade
Reinforcement= fy 500

These cubes were also cast in same manner as beams, using the mixer in laboratory and vibration was provided using table vibrator for gaining adequate strength and minimizing the voids /pore holes that could have affected adversely on reinforcement leading to high chances of corrosion, thus the cube samples were then cured in water tank and further they were also kept in active corrosion environment to see the change in resistivity of cubes as done in case of beams.

3. After casting of beams and cubes , three cylinders were also cast with same concret mix , but with different grade of reinforcement. One cylinder was provided with corroded bars where as other two cylinders were provided with fy 500 similar to the cube samples as shown below in figure 5and 5b.

Cylindrical Cube1: Size = Diameter 3"x6"[150mm Dia x150mm].
Concrete = M-20 grade
Reinforcement= fy 500

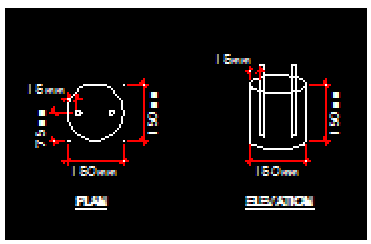


figure 5.Section and elevation of cylinder1.

Cylindrical Cube2: Size = Diameter 3"x6" [150mm Dia x150mm].
Concrete = M-20 grade
Reinforcement= Corroded bars

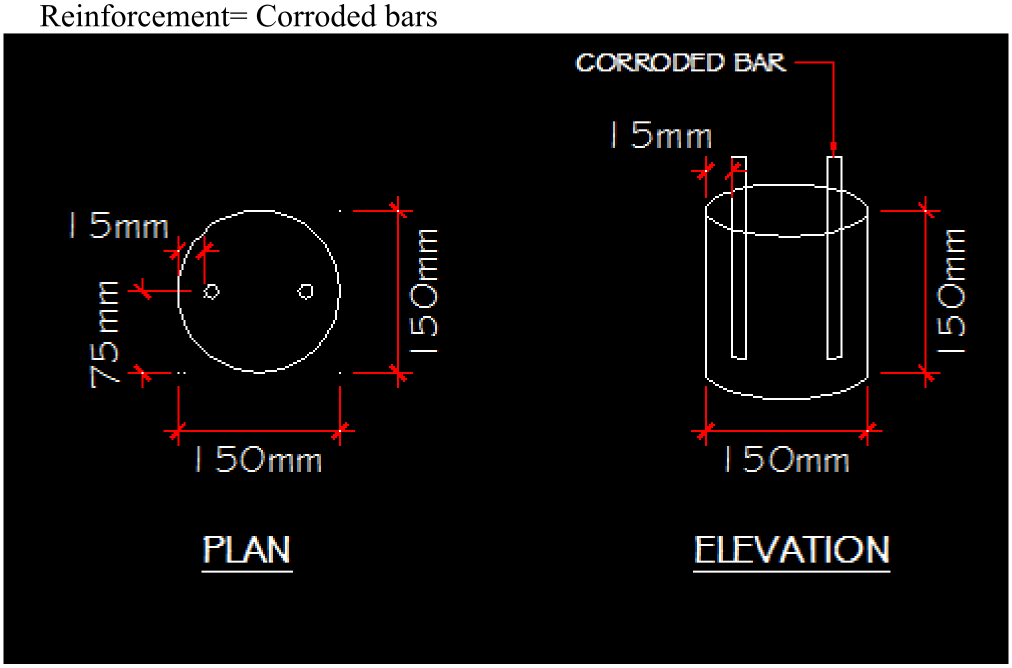


figure 5b .Section and elevation of cylinder2.

Cylindrical Cube3: Size = Diameter 3"x6"[150mm Dia x150mm]
Concrete = M-20 grade
Reinforcement= fy 500

DETAIL OF TESTING EQUIPMENT

In all the structural members shown above the resistivity is measured using resistivity meter (RESIPOD RESISTIVITY METER), This equipment enables us to gather the resistance of soil, concrete structures, steel etc. Resistivity meter provides extremely fruitful details and data about the state of a concrete structure. Resistivity meter is linked directly with the likelihood of corrosion and corrosion rate as shown above in table 2a and 3. For analyzing the effect of corrosion resistivity meter is certainly the most appropriate instrument which measures the effect of resistance of R.C.C structure in kilo ohm per cm (kilo ohm/cm).

Resisitivity of concrete , soil or any other material is measured in kilo ohm per cm , which signifies resistance offerd by any particular matreial . Resistance is measured in kilo ohm and it is parametrised as change or loss observable per unit centimeter which is the unit of resisitivity (kilo ohm per centimeter). The outer two probes of resistivity meter passes current to the surface and inner probes recieves them and the losses observed show the resistivity of material in kilo ohm per centimeter.

Resipod resistivity meter is having many applications as following:

- Estimation of the likelihood of corrosion
- Indication of corrosion rate
- Correlation to chloride permeability
- On site assessment of curing efficiency
- Determination of zonal requirements for cathodic protection systems
- Identification of wet and dry areas in a concrete structure
- Indication of variations in the water/cement ratios within a concrete structure
- Identification of areas within a structure most susceptible to chloride penetration
- Correlation to water permeability of rock

Resistivity meter is having a tall panel which is showing the reading of resistance of different R.C.C. structure, thE panel has different options to save the reading, eventually print the measurement etc. As if we touch the lower most part of resistivity meter known as probe to top of concrete surface which performs the analyzing task as a current is applied to outer probes and their potential difference is measured between inner probes as displayed in figure 6 below

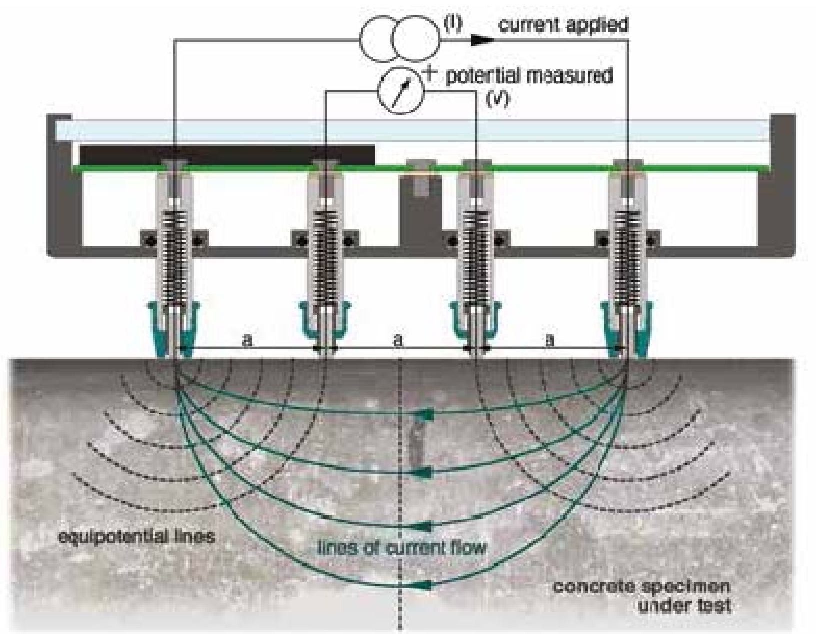


figure 6. Showing working of resisitivity meter.

Despite being extremely simple to use, Resipod provides a variety of features that are unique in a concrete surface resistivity instrument.

• Fully integrated surface resistivity instrument
• Wide measuring range (0 to 1000 kΩcm)
• Fast and accurate delivery of measuring results
• Highest resolution available for a surface resistivity instrument
• Meets the AASHTO TP 95-11 standard (38mm, 1.5” probe spacing)
• Current flow indication and poor contact indication
• Hold, save and delete function, with onboard memory
• USB connection and dedicated PC software
• Designed to float (waterproof according to IPX7)
• Allows variable probe spacing to be set
• Allows replacement of standard tips with accessories

Steps involved in testing through resistivity meter:

1. Initially it is very crucial to preset the instrument before use as it can follow any error due to last use if not switched off.

2. Probes of the resistivity meter are to be made in contact with concrete surface so as to close the circuit through the probes.

3. Outer probes provide a current through the surface

4. Measurement of potential drop is done using inner probes

5. Then finally the readings are observed.

TESTING PROGRAM PROCEDURE

The beams , cubes and cylinders are now evaluated individually and also in groups. Resistivity of beams is measured from second day of casting regularly initially the resistivity was enough to resist the effect of corrosion, but by use of sudden drying and wetting the beams and other structural members have become prone to corrosion due to decrease in resistivity from 22kohm / cm to nearly 5 k ohm /cm.Thereafter we have analyzed the effect of corrosion on daily basis in the presence of active environment .

Different structural members were also coupled in groups in various formats such as:

1. Beam + cube+ cylinders--------24v D.C supply
2. Cube + beam + cylinders --------24v D.C supply
3. cylinders + beam + cube--------24v D.C supply
4. Cube + cylinders + beam--------24v D.C supply
5. Beam + cylinders + cube--------24v D.C supply
   and
6. Cube + cylinders --------24v D.C supply
7. Beam + cube--------24v D.C supply
9. Beam + cylinders --------24v D.C supply

These structural members were then analyzed individually before giving Direct current output in which they show high sign of corrosion due to very less resistivity monitered by resipod resistivity meter.Subsequently these structural members are coupled in groups as described above the effect of d.c supply now play the significant role as we observe the drastic change in resistivity of nearly all structural members irrespective of their order of placement .

There are many steps to complete for the testing procedure but in brief they would be as:

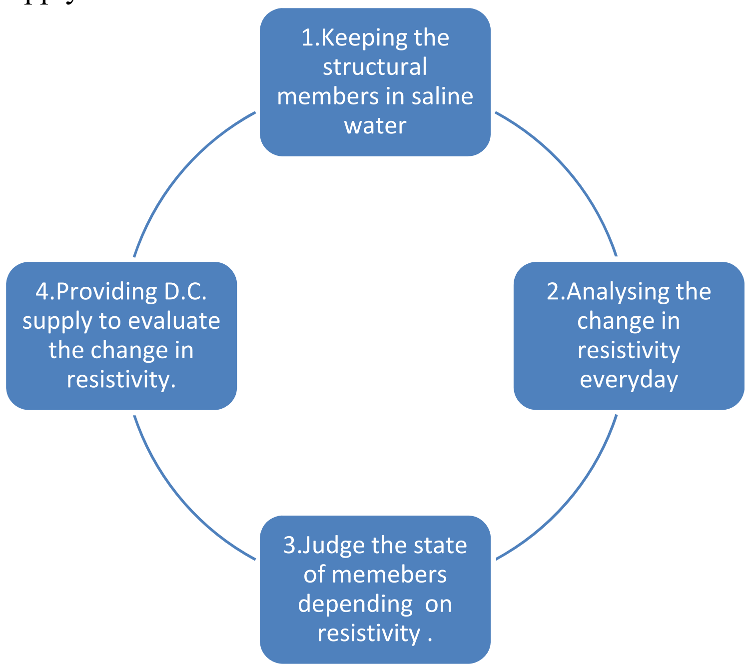
1. The most crucial aspect is to provide the required corrosion active environment to the beams, cubes etc so as the drop in resistivity is significant to allow the action of corrosion.

2. Testing program enables to get qualitative results only by coordinated and regular evaluation of results using resistivity meter. Thus we measured the change in resistivity every day.

3. The graph of resistivity on negative fall shows the effect of corrosion overtaking on structural member which causes the structure to corrode very easily

4. After getting the resistivity less than or equal to 5 kilo ohm per cm we provide D.C. supply to observe the change in resistivity

5. The final reading is taken on the basis of change in resistivity measured in the presence of direct current supply.



ASPECTS OF TESTING DIFFERENT STRUCTRAL MEMBERS:

To judge the difference in output in form of resistivity offered by different members either individually or in groups we have coupled different structural members with distinct shape , sizes and physical properties to evaluate the combined effect of corrosion on them and further the cross effect of d.c. supply which certainly resists or completely overcome the effect of corrosion on structural members coupled together or individually till the time d.c. supply is provided.

It becomes very difficult to analyze a practical structure as basic requirement of the project demands the structure to be corroded to observe the counter acting force of cathodic protection using d.c supply to increase the resistivity by controlling the flow of ions , thus to analyze the effect at most closest to live structures we have tried combination of different small structural members having distinct physical properties , which allow us practically to relate to a huge structure in which small members are connected directly or indirectly ,for ex in huge spans we have expansion joints which have two seprate vertical members but are indirectly joined as being part of a parent structure .

If one count on benefits of analyzing more than one member at a time, it would be that it enables us to gather the idea of losses or false effect that could take place in tall structures or huge structure or structure in which there are many sub components for example.

1. Small residential houses (G+1) having interconnected foundations.
2. Tall structures
3. Buildings with expansion joints
4. For purpose of architectural concern few high rise buildings are joined at some level for elevation purpose.

We have nearly tried all different members in all permutation and combination , the part of results is explained in later portion.

TEST FOR RESISTIVITY OF BEAM

As we have started our work of research initially on beams only , I ll elaborate step by step how we acclaimed to conclusion to do so and how we commenced this and what all hurdles we have to go through , starting by casting of three different beams with same physical properties but using different reinforcement as mentioned above and shown below in figure 7 .

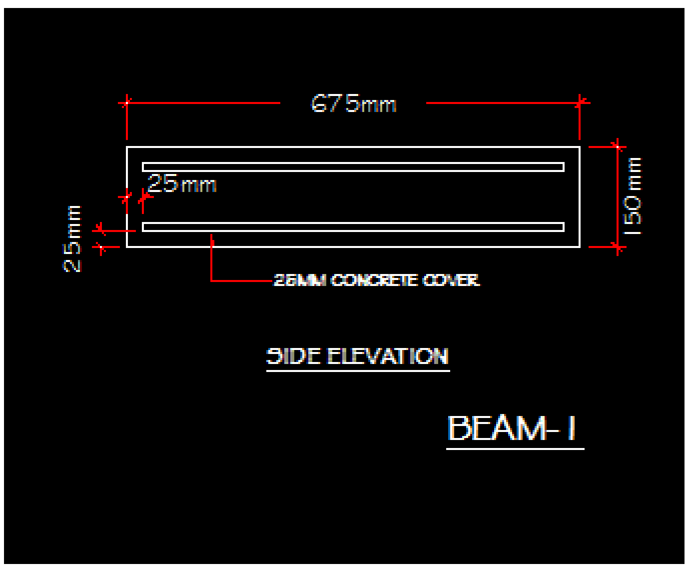


figure 7 Detail of beam elevation and section.

The beams are eventually checked every second day for measuring their resistivity when kept in normal laboratory environment temp (varying from 15 to 40 degree Celsius , humidity 10 to 20 percent) , so in these condition there was negligible change observed in the resistivity of beams in initial two weeks , so as per guided and discussed by my project in charge an artificial corrosion active environment was created by sudden wetting and drying of structural members for 3 weeks and change in resistivity was measured regularly and recorded in a tabular format as shown below in table 5.

Table 5 for recording resistivity of beam after equal interval of time.

TABLE FOR RESISTIVITY

	DATE	RESISTIVITY (KΩ/CM)	STRUCTURAL MEMBER
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

The observations show drastic change in resistivity which made the beams highly prone to corrosion, D.C supply was used on individual beams to see the effect of impressed current Cathodic protection and subsequently all the change was measured using resistivity meter and it was noted down in following manner :

To elaborate the steps used in test for resistivity on beams it could be divided in as following steps:

1. Casting of beams with different reinforcement.

2. Corroding the beams for decreasing its resistivity.

3. Analyzing all beams differently using resistivity meter to measure the effect of corrosion.

4. Providing d.c supply to check the effect of impressed current cathodic protection

TEST FOR RESISTIVITY OF CUBES

Similarly now we are casting three diffent cubes and cylinders and doing all the same steps as we have done in beams .The figure 8 , 9 and 12 elaborate the details of cubes and cylinders casted.Figure 10, 11, 13 shows the detal of cubes and cylinders when placed in saline water for early corrosion and in circuit in presence of direct current to resist corrosion.

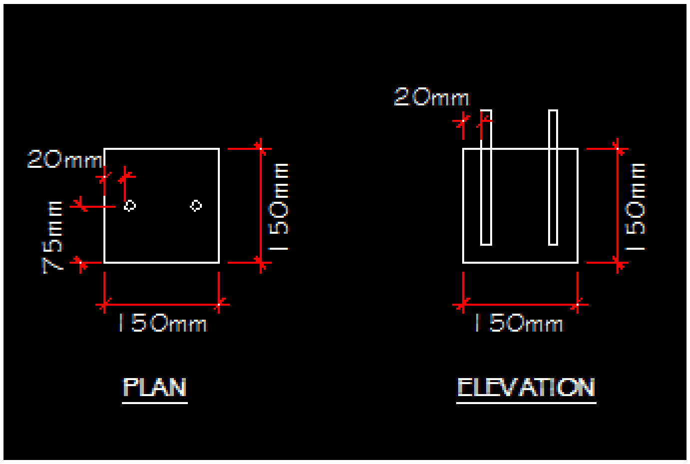


Figure 8 Detail of cube

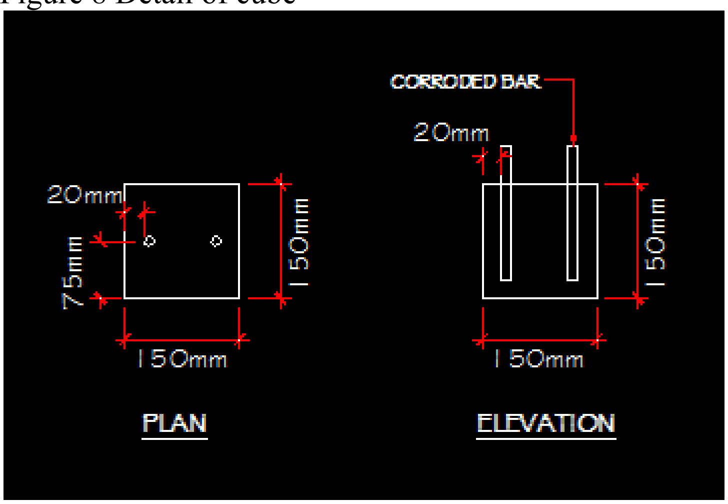


Figure 9 Detail of cube

Similarly as we have measured the resistivity in beams now we follow same steps in case of cubes and cylinders

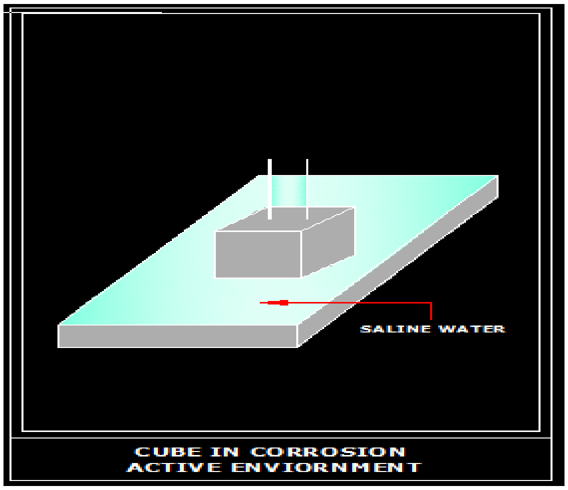


Figure 10 Detail of cube placed in saline water

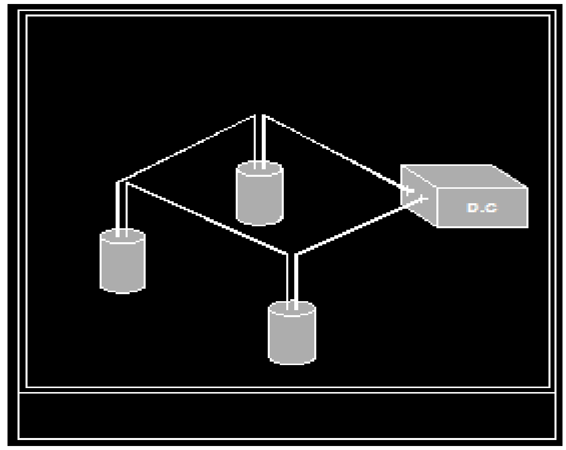


Figure 11 Detail of cylinders in pairing

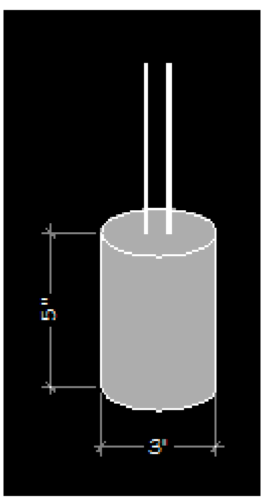


Figure 12 Detail of cylinder

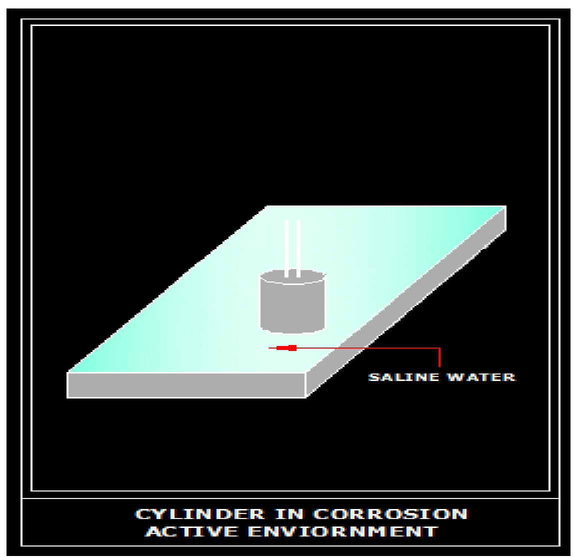


Figure 13 Detail of cylinder placed in saline water

TEST FOR EFFECT OF ICCP ON COMBINATION OF BEAM, CUBE AND C.CUBE

After evaluating the effect of all the structural members individually , now as discussed and guided by concern project in charge .I initiated to couple different structural members and followed the same procedure to evaluate the effect of corrosion as described above with the use of combinations shwon above on page no 34 : , which are elaborated diagramatically in figure 14,15,16 shown below ;

These combinations are in detail shown diagrammatically as following:

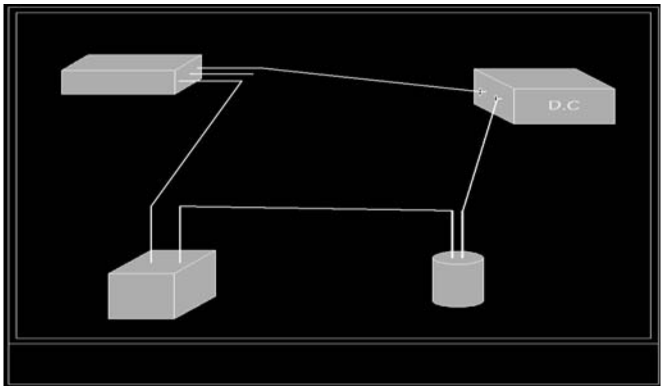


Figure 14

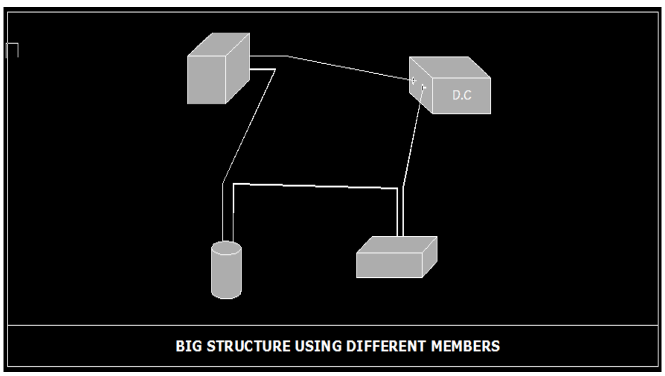


Figure 15

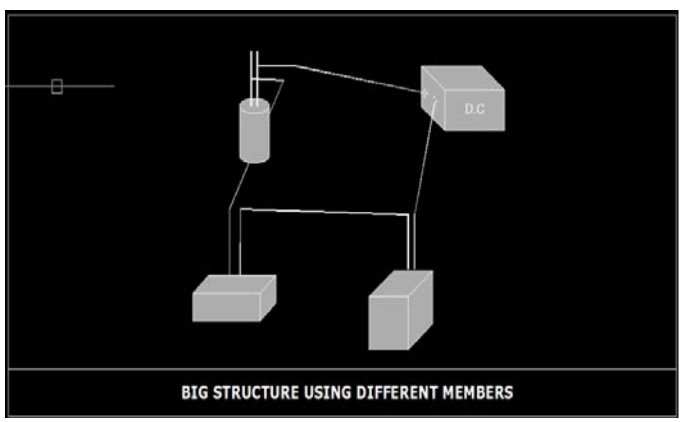


Figure 16

Chapter 5.RESULTS AND CONCLUSSIONS

5.1 Resistivity of beams and other structural members in first week of casting:

As mentioned above the procedure in detail, the resistivities of beams were measured on weekly and daily basis depending on the condition of beams. In initial days there was not much changes observed as beams were kept in normal atmosphere and the resistivites of different beams were as shown below in Table 6 and 7.

Table 6 . Resistivity of beams is not decreasing much as in normal atmosphere).

	BEAM-1	BEAM-2	BEAM-3
DATE	RNF. FE500	MILD STEEL	CORRODED STEEL
19th jan.	21	22	21
22nd jan.	22	21.3	20
25th jan.	20	21.7/21.8	22

Later as we have to analyze the effect of active environment on our structural members we tried sudden wetting and drying , after this action we find observable major differences in resistivities .Therefore the beams become highly corrosive , so we applied dc supply to evaluate and govern the effect of cathodic protection on beams . The table below elaborated the detail better :

Table 7(Sudden drop in resistivity is observable as the samples are placed in saline water)

	BEAM-1	BEAM-2	BEAM-3
DATE	RNF. FE500	MILD STEEL	CORRODED STEEL
19th jan.	21	22	21
22nd jan.	22	21.3	20
25th jan.	20	21.7/21.8	22
1st feb.	19.5	21	19
4th feb.	19	21	17.5
6th feb.	19.5	18	16
8th feb.	18.3	14	17
12th feb.	17.6	16.3	13
15th feb.	16.4	15	15
20th feb.	14.3	12	13.6
25th feb.	15.2	11	09
28th feb.	11	09.8	08.5
2nd mar.	09.3	07.6	07.6
6th mar.	07.6 → 18.0	05.3 → 19.0	04.3 → 18.0
9th mar.	07.6 → 17.5	04.8 → 18.0	04.3 → 18.0

Similarly we have governed the resistivies of small structural members like cubes and cylinders which also show nearly similar graphs of resistivity on application of different active corrosion environment modes and further d.c. supply . Which is shown in table 8, 9 and 10.

Table 8 .Measurment of resistivity of cylinders .

			CYLINDER-1	CYLINDER-2
SALINE WATER		DATE	RNF. FE500	CORRODED STEEL
	1	28th FEB.	25.2 (KΩ/CM)	23.8 (KΩ/CM)
	2	3rd MARCH	24.9 (KΩ/CM)	22.5 (KΩ/CM)
	3	7th MARCH	22.3 (KΩ/CM)	21.8 (KΩ/CM)
	4	12th MARCH	18.6 (KΩ/CM)	18.2 (KΩ/CM)
	5	17th MARCH	15.3 (KΩ/CM)	15.5 (KΩ/CM)
	6	20th MARCH	11.4 (KΩ/CM)	10.9 (KΩ/CM)
	7	28th MARCH	9.8 (KΩ/CM)	9.5 (KΩ/CM)
	8	2nd APRIL	9.1 (KΩ/CM)	8.9 (KΩ/CM)
	9	4th APRIL	8.8 (KΩ/CM)	8.3 (KΩ/CM)
	10	8th APRIL	8.2 → 22.8	8.2 → 23.0

Table 9. Measurment of resistivity of cubes .

			CUBE-1	CUBE-2
	DATE		RNF. FE500	CORRODED STEEL
SALINE WATER	1	3rd MARCH	24.8 (KΩ/CM)	22.6 (KΩ/CM)
	2	7th MARCH	24.3 (KΩ/CM)	21.3 (KΩ/CM)
	3	12th MARCH	23.2 (KΩ/CM)	20.6 (KΩ/CM)
	4	17th MARCH	20.1 (KΩ/CM)	19.3 (KΩ/CM)
	5	20th MARCH	18.6 (KΩ/CM)	16.5 (KΩ/CM)
	6	28th MARCH	15.4 (KΩ/CM)	13.3 (KΩ/CM)
	7	2nd APRIL	13.2 (KΩ/CM)	9.6 (KΩ/CM)
	8	4th APRIL	10.8 (CORROSION PRONE)	8.8 (KΩ/CM)
	9	8th APRIL	8.3 → 22.5	7.9 → 22.0

For small structural members and beams, the results show that in normal condition the change in resistivity is very low as the effect of humidity and moisture in normal circumstances is not that drastic, where as when we keep the cubes and other structural members in corrosion active environment, a sudden decrease in resistivity is observed as shown in above result table 7, 8 and 9.

The effect of corrosion is nearly same on all samples ,the diffrence in lower most resistance achieved by beam is due to the time for which we have placed the beam samples in saline water , whereas cube and cylinderical samples are showing nearly same drop in resistivity , so it can be understood from above tabular data that similar sized structural members when kept in same atmospherical condition show nearly same drop in resistivity due to effect of corrosion . The effcet of cathodic protection enables to safegaurd all the members of diffrent shapes and sizes as their is not much change in sizes. If we want to study the effct of cathodic protection on a beam with 450 mm drop (size 300 mmx450 mm) it should also show approximately similar graph of resistivity whereas any other structure with even more size can show some diffrence in change of resistivity under the action of cathodic protection.

The degraded effect of corrosion leads the structural member to most suspectable level of corrosion, then we apply cathodic protection using artificial power source (D.C supply), which controls the effect of corrosion on structural member by controling the flow of ions, thus safeguards the member from action of corrosion till it is supplied with continuous d.c supply.

5.3 ANALYSIS OF RESISTIVTY WHEN DIFFRENT STRUCTURAL MEMBERS COMBINED.

1. Beam + cube+ c. cube
2. Cube + beam + c cube
3. c. cube + beam + cube
4. Cube + c.cube+ beam
5. Beam + c.cube+ cube

And

6. Cube + c.cube
7. Beam + cube
9. Beam + c. cube

As by the analysis of individual structural members we evaluated the effect of cathodic protection , now we are combining different combination of beams , cubes and c. cubes for the evaluation of cathodic protection's effect on a big structure or its effect when many small structures are to be analised altogether.

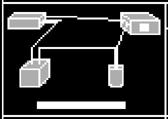
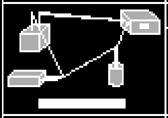
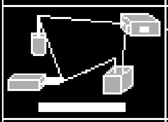
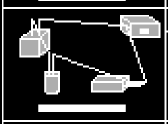
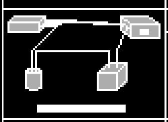
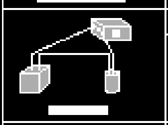
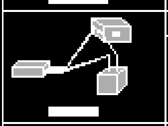
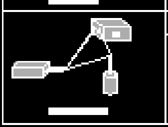
The results in table 10 below show the effect in change of resistivity in combination of different structural members :

The above results evaluated by different combinations show a very minute change in resistivity all the corrosion active samples were used in different permutations and combinations , the change in resistivity could be attributed to the difference in condition of different samples it may be due to physical properties shape , size etc or the effect of corrosion depending on individual sample.

Thus , this analysis by combination of different structures is giving an idea that under the effct of cathodic protection the resistivity of structural member increases drastically keeping the structure safe from action of corrosion till the structure is connected to continuous direct current supply.

Combination of different structures were done randomly so as to analyze the effect of cathodic protection on couple of different structures , which enables us to derive result measuring resistivity at different phases in normal atmosphere and corrosion active environment and then finally when we provide continuous direct current supply.

TABLE-10. Measurment of Resistivity in combination of diffrent structural members

			RESISTIVITY (KΩ/CM)						
		DATE	BEAM	CUBE	C.CUBE	D. C. SUPPLY	BEAM	CUBE	C.CUBE
	1	15/07/2014	4	8.6	8.6	12+12	14.6	19.8	19.2
	2	16/07/2014	4.2	8.7	9.1	12+12	18.3	19.8	20.1
	3	16/07/2014	4.1	8.7	9.0	12+12	18.1	18.9	20.1
	4	16/07/2014	4.3	8.2	8.9	12+12	18.1	19.0	19.8
	5	16/07/2014	4.2	8.3	8.6	12+12	18.4	19.8	19.5
	6	16/07/2014	---	8.2	8.3	12+12	---	20.0	20.3
	7	16/07/2014	4.3	8.1	---	12+12	18.7	20.1	---
	8	16/07/2014	4.1	---	8.2	12+12	19.0	---	20.2

Conclussion:

1.Only 2 to 3 percent change is observed due to change in size and shape of structural member in respect of change in resistivity in corrosion active atmosphere. Which we analyzed by measuring resistivity of diffrent structural members in similar environmental condition.

2. Steel of different yield strength was used in similar shaped structures and the difference was observable in respect of resistivity offered by individual steel reinforcement . Thus it can be understood that corroded steel was having the least resistivity when all three samples of fy 500, fy 415 and corroded steel were kept in same active environment as ellaborated in table 8 and 11 in detail.

3. Drastic change in resistivity is observable when the reinforced concrete cement samples are kept in corrosion active environment keeping part of the reinforcement exposed.The results in table 6 , 7 , 8 , 9 and 10 show the change in resistivity with time.

4.The direct current supply should be continuous for complete safety of structure ,as cathodic protection enables to secure the reinforcement only till power supply is present .The direct current supply leads to change in resisitivty from 7.6 to 18 kilo ohm per cm and 5.3 to 19 kilo ohm per cm but only till direct current supply is present.

	BEAM-1	BEAM-2	BEAM-3
DATE	RNF. FE500	MILD STEEL	CORRODED STEEL
2nd mar.	09.3	07.6	07.6
6th mar.	07.6 → 18.0	05.3 → 19.0	04.3 → 18.0
9th mar.	07.6 → 17.5	04.8 → 18.0	04.3 → 18.0

5.With coupling of direct structures we analyzed that n numbers of small structures connected directly or indirectly can be protected with one power source which can minimise the expenses of impressed current cathodic protection as shown in table 10 .

FUTURE SCOPE

1. Diffrent small structure were analyzed as part of research , for better and more clarity on understanding the behavior of actual structure one can test on structural members with bigger size .

2. By practically governing the changes on a small old or new structure the behavior of reinforcement and structure can be analyzed even better.Which would enable us to to relate the effect of cathodic protection on existing structure.

3.Diffrent tanks can be used for placing structural member in them to analyze the behavior of structure in sea or marine areas.

4. Apart then directly using batteries we can convert alternating current and provide variations to see the effect and measure resistivity.

5. An actual construction site should be selected for research and with providing current at one end of structure we can govern the changes at other.

6 We can analyze big size beams and retaining wall to attain more clarity to protect the structure using cathodic protection.

7. By varying salt content from 10 to 25 wt % we can observe the changes in effect of corrosion.

REFRENCES

[1] D.A. Koleva , Z. Guo, K. Van Breugel, J.H.W. de Wit, Conventional and pulse cathodic protection of reinforced concrete: electrochemical behaviour of thesteel reinforcement after corrosion and protection, Mater. Corros. 60 (2009)344–354.

[2] BS EN 12696:2000, Cathodic Protection of Steel in Concrete, British Standards Institution, London, 2000.

[3] M. Pourbaix, Atlas of Electrochemical Equilibrium in Aqueous Solutions, NACE International, Houston, TX, USA, 1996.

[4] B.S Wyatt, Developments in Cathodic Protection of Steel in Concrete: Concrete Bridge Development Group, Annual Conference: Eurocodes and Innovation,Oxford, 2009.

[5] G.K. Glass, J.R. Chadwick, An investigation into the mechanisms of protection afforded by a cathodic current and the implications for advances in the field of cathodic protection, Corros. Sci. 36 (1994) 2193–2209.

[6] J.P. Broomfield, J.S. Tinnea, Cathodic Protection of Reinforced Concrete Bridge Components, Final Report. ID No: SHRPCUWP92618, 1992.

[7] F.J. Presuel-Moreno, A.A. Sagüés, S.C. Kranc, Steel activation in concrete following interruption of long-term cathodic polarisation, Corrosion 2002 (Paper no. 02259).

[8] G.K. Glass, B. Ready, L. Clark, Making reinforced concrete immune from chloride corrosion, Proc. Inst. Civ. Eng. Constr. Mater 160 (2007) 155–164.

[9] R.E. Stratful, The corrosion of steel in a reinforced concrete bridge, Corrosion 13 (1957) 43–48.

[10] B. Elsener, Half cell potential measurements–potential mapping on reinforced concrete structures, RILEM TC 154-EMC: electrochemical techniques for measuring metallic corrosion, Mater. Struct. 36 (2003) 461–471.

[11] BA 35/90, Inspection and Repair of Concrete Highway Structures, British Standards Institution, London, 1990.

[12] J.P. Broomfiled, Corrosion of steel in concrete, understanding, investigation and repair, E & F. N. Spon, London, 1997.

[13] M. Stern, Al.L. Geary, Electrochemical polarisation I: a theoretical analysis of the shape of polarisation curves, J. Electrochem. Soc. 104 (1957) 56–63.

[14] D.D. McDonald, M.C.H. McKubre, Electrochemical impedance techniques in corrosion science, in: F. Mansfeld, U. Bertocci (Eds.), Electrochemical Corrosion Testing ASTM STP 727, 1981, pp. 110–149.

[15] R. Polder, A. Tondi, R. Cigna, Concrete Resistivity and Corrosion Rate of Reinforcement, TNO Report 93-BT-r0170, TNO Delft, 1993.

[16] C. Andrade, C. Alonso, Test methods for on-site corrosion rate measurement of steel reinforcement in concrete by means of the polarisation resistance method, RILEM TC 154-EMC: electrochemical techniques for measuring metallic corrosion, Mater. Struct. 37 (2004) 623–643.

[17] Concrete Society, Technical Report 60, Electrochemical Tests for Reinforcement Corrosion, Surrey, UK, 2004.

[18] C. Andrade, C. Alonso, On-site measurements of corrosion rate of reinforcements, Constr. Build. Mater. 15 (2001) 141–145.

[19] G.K. Glass, A.M. Hassaein, N.R. Buenfeld, Obtaining impedance information on the steel concrete interface, Corrosion 54 (1997) 887–897.

[20] G.K. Glass, A.C. Roberts, N. Davison, Hybrid corrosion protection of chloridecontaminated concrete, Proc. Inst. Civ. Eng. Constr. Mater. 161 (2008) 163–172.

[21] R. Polder, W.H.A. Peelen, B.T.J. Stoop, E.A.C. Neeft, Early Stage Beneficial Effects of Cathodic Protection in Concrete Structures, Nice, France,

[22] Concrete Bridge Development Group. A case study of cathodic protection using sacrificial anodes on Queen's Park and Albert Royds street bridges. Technical paper 11. Camberley: Concrete Bridge Development Group; 2006.

[23] The Concrete Society. Cathodic protection of reinforced concrete. Technical report 36. Camberley: The Concrete Society; 1989.

[24] Highways Agency. Cathodic protection for use in reinforced concrete highway structures. BA 83/02. London: The Stationery Office; 2002.

[25] Pearson S, Patel RG. Repair of concrete in highway bridges – a practical guide. Application guide AG43. Crowthorne: TRL Limited; 2002.

[26] The Concrete Society. Model specification for cathodic protection of reinforced concrete. Technical report 37. Camberley: The Concrete Society; 1991.

[27] Bertolini L, Elsener B, Pedeferri P, Polder RB. Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair. Weinheim: Wiley-VCH; 2004.

[28] Tilly GP, Jacobs J. Concrete repairs – performance in service and current practice. Bracknell: IHS BRE Press; 2007.

[29] Grefstad K. Cathodic protection applied on Norwegian concrete bridges. Experience and recommendations. Eurocorr05. Lisboa; 2005. CD-ROM.

[30] Nerland OCN, Eri J, Grefstad KA, Vennesland Ø. 18 years of Cathodic Protection of Reinforced Concrete Structures in Norway – facts and figures from 162 installations. Eurocorr07, Freiburg; 2007. CD-ROM.

[31] Polder RB. Cathodic protection of reinforced concrete structures in The Netherlands – experience and developments. HERON 1998;43(1):3–14.

[32] Wenk F, Oberhänsli D. Long-term experience with cathodic protection of reinforced concrete structures, Eurocorr07, Freiburg; 2007. CD-ROM.

[33] Tinnea JS, Cryer CB. Corrosion control of Pacific coast reinforced concrete structures: a Summary of 25 years experience. In: First international conference on heritage and construction in coastal and marine environment MEDACHS08, Portugal; 2008. CD-ROM.

[34] Christodoulou C, Glass G, Webb J, Austin S, Goodier C. Assessing the long term benefits of impressed current cathodic protection. Corros Sci 2010;52: 2671–97. [9] CEN. Cathodic protection of steel in concrete. EN 12696; 2000.

[35] Polder RB, Peelen WHA. Service life aspects of cathodic protection of concrete structures. In: Grantham M, editor. Concrete repair. A practical guide. London: Taylor and Francis; 2011.

[36] Mietz J, Fischer J, Isecke B. Cathodic protection of steel-reinforced concrete structures – results from 15 years' experience. Mater Performance 2001; 40(12):22–6.

[37] Kalbfleisch JD, Prentice RL. The statistical analysis of failure time data. 2nd ed. New Jersey: John Wiley & Sons; 2002.

[38] Schuten G, Leggedoor J, Polder RB, Peelen WHA. Cost aspects of cathodic protection: a review after 14 years of operation. In: Raupach M, Elsener B,Polder R, Mietz J, editors. Corrosion of reinforcement in concrete, mechanisms, monitoring, inhibitors and rehabilitation techniques, European Federation of Corrosion Publication 38. Cambridge: Woodhead Publishing Limited; 2007.

[39] Bertolini, L., Bolzoni, F., Pastore, T. and Pedeferri, P. Cathodic prevention of reinforced concrete structures. In Proc. IV Corrosion Symposium, Otunbul Technical University, Istunbul, *25-26* October 1994

[40]Pedeferri, P. Cathodic protection of new concrete constructions. In Proc. Int. Conf: Structurul Improvement through Corrosion Protection of Reinjkced Concrete*,* Institute of Corrosion. London, 1992.

[41] Jia JX, Song G, Atrens A, St John D, Baynham J, Chandler G. Evaluation of the BEASY program using linear and piecewise linear approaches for the boundary conditions. JMater Corros 2004;55(11):845–52.

[42] Strong GE, Adey RA, Rudas KS. Computer prediction of straycurrent corrosion. In: Proceedings of the Australian corrosion conference. 1996.

[43] Holser RA, Prentice G, Pond RB, Guanti RJ. Current distributions in galvanically coupled and cathodically protected tubes. Corrosion 1992;48(4):332–40.

[44] Orazem ME, Esteban JM, Kennelley KJ, Degerstedt RM. Mathematical models for cathodic protection of an underground pipeline with coating holidays: part 2—case studies of parallel anode cathodic protection systems. Corrosion 1997;53(6):427–36.

[45] Purcar M, Van den Bossche B, Bortels L, Deconinck J, Wesselius P. Numerical 3-D simulation of a cathodic protection system for a buried pipe segment surrounded by a load relieving U-shaped vault.Corrosion 2003;59(11):1019–28.