STUDY ON PERFORMANCE OF SELF REGULATING SACRIFICIAL GALVANIC ANODES WITH AND WITHOUT PRECONDITIONING AGAINST CONTROL SPECIMEN AND USING ACCELERATED CORROSION

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ABSTRACT

The increasing number of reinforced concrete structures affected by corrosion makes the study of their protection an import parameter. Usage of different types of surface coatings on rebars for the corrosion protection has not proved to be a reliable system on account of many reasons like reduction in bond stress between the concrete & rebar and so on. The standard procedure of rehabilitation of corrosion affected structural elements. viz., chipping the cover concrete, exposing the rebar, cleaning rebars, applying corrosion protection coating to the rebar, providing formwork, pumping of micro concrete, etc becomes labour intensive and uneconomical in addition to a lot of disturbance caused to the occupants. Hence, sacrificial anodes are being increasingly used during the rehabilitation of corrosion affected Reinforced Concrete (RC) structures. The self regulating anodes comprise of zinc metal covered with porous matrix, which sacrifices itself and protects the corrosion of rebar. The paper presents the results of the study carried out on the performance of sacrificial galvanic anodes installed in RC structural elements with and without preconditioning methods.

1. INTRODUCTION

Reinforced concrete is a versatile, economical, successful and commonly used material. It is durable and strong, performing well throughout its service life. Today, in India we are placing new concrete to the tune of approximately 1 m^3/ person nationally, which is a large quantity. If we take stock of concrete placed in past years, then an educated guess is about

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25 m^3 / person could be already in place. This is a huge inventory. A large quantity of this concrete is over 10 years old. Most of this concrete was site mixed and without many controls and as a result more susceptible to carbonation, chloride attack, loss of alkalinity and attack of other aggressive chemicals.

In India, where approximately 80% of the rainfall takes place in the two monsoon months, rusting related problems are very common, especially in industrial, infrastructure and residential structures. India has also a very long coastal line where marine conditions prevail. Typically, a building requires major restoration within a decade approximately. The present practice of repairs in India is focused towards the delaying of rehabilitation/ restoration.
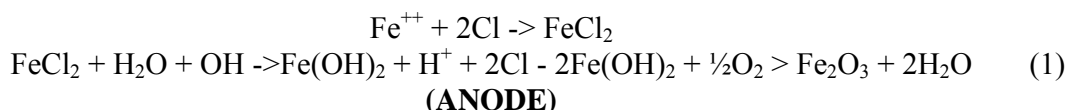
1.1 Carbonation
The high pH of concrete passivates steel reinforcement from getting corroded. The carbon dioxide/sulphur dioxide present in the atmosphere gets dissolved in to water and forms weak carbonic/ sulphuric acid and enters the concrete through micro pores reducing the pH, resulting in loss of passivation layer around the reinforcement. The reinforcement starts getting corroded resulting in the rust. The volume of rust is more than eight times of the original volume of the metal creating bursting pressure in the concrete mass. The build-up of the pressure eventually cracks the concrete and makes the access for ingress of water and other water dissolved agents easy. The quicker access aggravates the corrosion and structure starts deteriorating rapidly.

Spalling of the concrete cover and formation of brown coloured rust is a visual indication of the carbonation attack. The carbonation depth can be assessed by phenolphthalein liquid. The reaction is at its best at 50 – 75% relative humidity. The corrosive reaction is expressed as $CO_2+H_2O+Ca(OH)_2 >CaCO_3+H_2O$.

1.2 Chloride attack
The main source of chlorides is the contaminated water or aggregates used during construction and the marine environment – direct contact with sea water or through wind borne chlorides in the splash zone. Chlorides ions first attack Fe_2O_3 - the passivating ferrous oxide layer on the steel reinforcement. Once reinforcement loses its passivation layer, it is highly susceptible to electro-chemical corrosion further induced by diffusion of more chloride ions. The water dissolved chloride ions forms electrochemical corrosion cell and establishes anodic and cathodic sites on the rebar.

The electro-chemical corrosion results in to pitting corrosion – reduction in the cross section of the rebar at specific sites without noticeable deterioration of the concrete cover. The hidden reduction in the cross-section of the reinforcement can result in to sudden failure of the structural member - making this as one of the most dangerous deterioration in the concrete structure. The corrosive reactions are expressed as:

$$Fe^{++} + 2Cl -> FeCl_2$$
$$FeCl_2 + H_2O + OH ->Fe(OH)_2 + H^+ + 2Cl - 2Fe(OH)_2 + ½O_2 > Fe_2O_3 + 2H_2O \quad (1)$$
(ANODE)

$$½O_2 + H_2O + 2e -> 2OH- \quad (2)$$
(CATHODE)

There is no "net use" of chloride ions during the corrosion process. Therefore, once enough chloride ions reach the steel to break the passivation layer, only water, oxygen and a conductive medium is needed to maintain the corrosion reaction. Since corrosion is a chemical reaction, temperature plays an important role in the process. The higher the temperature the faster the corrosion reaction occurs. The general rule for the rate of chemical reaction is that for every 25°F increase, the reaction rate doubles. Concrete repair and protection projects do not satisfy performance criteria in most of the cases. One of the largest inventories of Concrete structures in the world is with U.S Army Corps of Engineers and their experience is that barely 50% of the repairs perform satisfactorily and remaining ones fall into either fair or poor or failed category due to the problems in design, installation and materials. In India, due to unorganized nature of the industry and outdated methods of execution, the performance would be still marginal and can be vague.

This performance will further get affected depending on aggressive conditions varying from region to region in India. However, the corrosion of reinforcing steel in concrete is becoming an issue in the durability of the concrete structures, as engineers are struggling hard to maintain aging infrastructures. Usually, steel embedded in concrete becomes passivated due to the initial high alkalinity (12<pH<13) of the pore solution. However, the protective film is destroyed and the reinforcing steel is passivated when sufficient chloride ions have penetrated to the reinforcement or when the pH of the pore solution drops to low values due to carbonation. Corrosion in the form of rust formation and/or loss in cross section of the reinforcing steel occurs in the presence of oxygen and water [1].

The corrosion of steel in concrete essentially is an electrochemical process, where at the anode, iron is oxidized to iron ions that pass into solution and at the cathode, oxygen is reduced to hydroxyl ions. Anode and cathode form a short-circuited corrosion cell, with the flow of electrons in the steel and of ions in the pore solution of the concrete. The corrosion between actively corroding areas of the reinforcing steel and passive areas is of great concern because it results in very high local anodic current densities with corrosion rates of 0.5 to 1 mm/year [2]. The resulting local loss in cross section has dangerous implications for the structural safety, if the corroded steel is located in a zone of high tensile stresses or shear stresses.

The most obvious consequence of lack of durability in reinforced concrete is the corrosion of the steel reinforcement, a topic that has been widely studied and reported [3, 4]. Many new systems and materials have been developed to delay the onset of corrosion and to increase durability [5]. However, all the new systems have limited success in delaying the onset of corrosion. From the view of economical and engineering points, quantitative assessment of corrosion is also important. The coating of conventional reinforcement [6,7] is designed to provide the steel with corrosion protection beyond that afforded by the cover concrete. Figure 1 shows the service life model for design life.

One of the commonly used techniques to improve the corrosion resistance of RC structures is the installation of the self regulating anodes in the new construction as well as the distressed structural elements during their rehabilitation. Sacrificial anodes can be made of aluminum, magnesium and zinc alloys. However, aluminum and magnesium anodes have expanding products, causing severe cracking in the overlay. Thus zinc alloy becomes a choice for making anodes embedded in concrete in many applications [8-10].
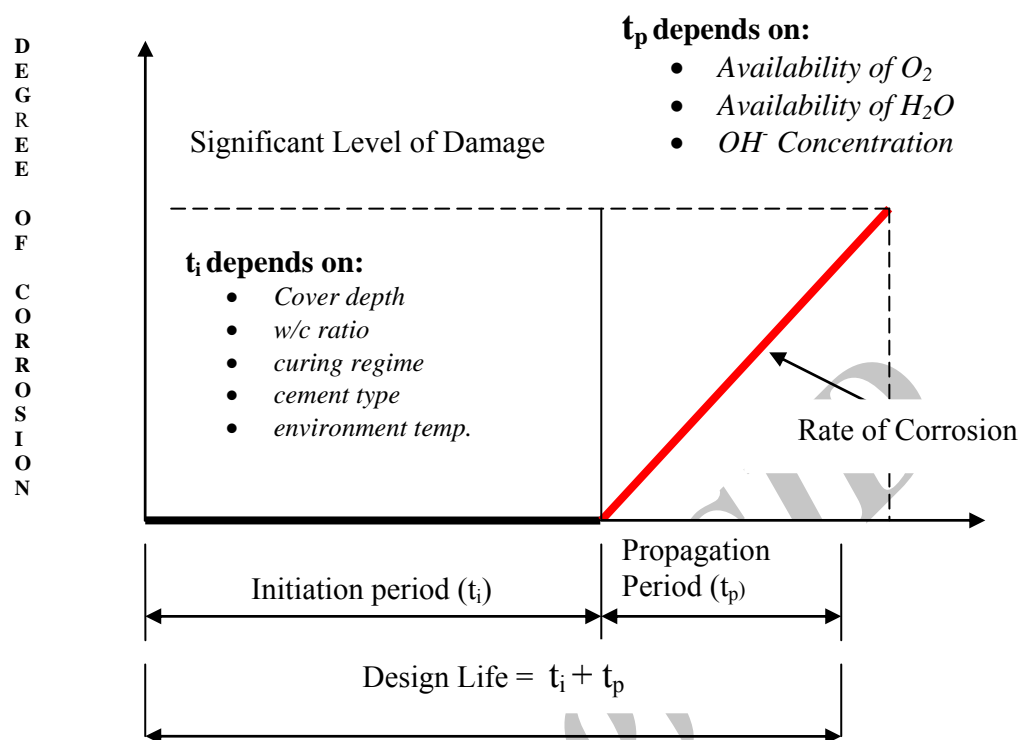
Figure 1. Service life model for design life

However, the conditioning of the self regulating anodes before they are installed in the structural elements plays a vital role in improving the corrosion resistance of the rehabilitated structures. There have not been many studies on the preconditioning effect of self regulating anodes installed in the new/distressed RC structures for the successful implementation of the rehabilitation technique.

In order to qualitatively and quantitatively understand the mitigation of corrosion due to the usage of sacrificial galvanic anodes, two types of specimens were cast in addition to the control concrete specimen, in which protection was not given to the rebar against corrosion. The effectiveness of the conditioning of the self regulating anodes was assessed through the impressed current technique. The performance of the self regulating anodes was monitored and corrosion is expressed as a percentage of loss in weight of the rebars in comparison to the control specimen. The paper describes the fundamental process involved in rebar corrosion, impressed current technique, specimen selection, test procedure, results and discussions of the experimental investigations.

2. GALVANIC PROTECTION

Galvanic corrosion protection methods were originally developed in the 1820s. Over the years, galvanic corrosion protection systems have been widely used to protect underground steel structures, such as, pipelines and tanks. Galvanic protection systems were first used in

reinforced concrete structures around 1960. Recent technological advancements in the developments of galvanic anodes have led to a significant increase in their use for protecting reinforcing steel in concrete structures.

2.1 Sacrificial passive protection systems
The following are some of the sacrificial protective systems commonly used in the industry:
   (1) Zinc sheet anodes, precoated with a conductive hydrogel adhesive, are applied to the surface of the concrete. The formed anode is called zinc hydrogel anode and its appearance is improved by coating with various paints.
   (2) Zinc or zinc alloys are sprayed to the concrete using arc spray or flame spray equipment.
   (3) Embedded galvanic anodes are embedded within the repaired concrete and 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.

2.2 Impressed current cathodic protection
The impressed current cathodic protection systems contain an anode, a DC power source, and connecting cables. Various types of these systems based on the anode installation and its application are as follows:
   (i)   Surface-mounted anodes without overlays are mounted on the surface of the concrete and do not require a cementitious overlay. However, the wear resistance of the system is reduced.
   (ii)   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.
   (iii) Plate-type anodes consist of manufactured anode plates glued to the concrete surface.
   (iv)   Surface-mounted anodes with overlays are generally used on horizontal surfaces and require a cementitious overlay of 13 mm minimum thickness.
   (v)   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.
   (vi)   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.
   (vii) Embedded anodes system is embedded in the surface of the concrete or is placed at the level of the reinforcement in new construction.
   (viii) 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.
   (ix)   (ix) Anodes can be placed at the level of the reinforcement during new construction. This anode must not have direct contact with the reinforcing steel

2.3 Zinc
Zinc comprises an estimated 0.004% of the Earth's crust and ranks 25th in order of material

abundance in the Earth. Zinc's most remarkable quality is its natural capacity to protect. By protecting steel against corrosion, zinc protects buildings, automobiles, ships and steel structures of every kind from corrosion by the atmosphere, water and soil. By protecting against corrosion and its costly effects, zinc extends the life of steel, thus protecting investments. A typical galvanized coating can now be expected to last 70 to 150vyears without maintenance in most urban and rural atmospheres. Galvanized steel lasts longer today than it did 20 years ago. Because of environmental laws, our air is cleaner and less contaminated with corrosive emissions.

Zinc is 100% recyclable. Over 80% of the zinc available for recycling is currently recycled. More than one-third of the zinc consumed in North America is produced from recycled materials. Due to the long lifespan of most zinc-coated products like galvanized steel, which in some cases may last maintenance-free for over 100 years, much of the zinc produced in the past is still in use. Zinc makes the average automobile last longer-17 pounds of zinc protect it from rust, 20 pounds are used to make zinc die-cast parts like door handles and locks, and each tire contains about 1/2 pound of zinc, needed to cure rubber.

2.4 Sacrificial zinc anodes

Sacrificial anodes used for galvanic protection are typically constructed using aluminum, magnesium or zinc. For reinforced concrete applications, zinc has become the most common sacrificial anode used presently. There are several reasons for the usage of zinc.

a) Zinc has high corrosion efficiency i.e. high percentages of the electrons that are discharged when the zinc corrodes are available to protect the steel.

b) As zinc corrodes, it has a relatively low rate of expansion compared to other metals including steel. This makes zinc anodes particularly suitable for application where the anodes are embedded in to the concrete structure.

c) Zinc anodes are suitable for use with prestressed and/or post-tensioned concrete because their native potential is generally not sufficient to generate atoms or cause hydrogen embitterment in a concrete environment.

Zinc anodes are covered with a precast mortar matrix saturated with lithium hydroxide (LiOH), which increases the pH around the zinc to be in the range of 14 to 14.5. In this environment, the corrosion by-products are soluble and do not form a solid oxide film on the surface of the zinc. These types of system are referred to as "alkali-activated" system. These anodes are designed to be tied directly to the reinforcing steel to extend the life of concrete patch repairs.

Galvanic anodes work on the principle of sacrificial protection. When two dissimilar metals are placed in an electrolyte (in this case within concrete) the most active metal (zinc) will sacrifice itself to protect the more noble (less active) reinforcing steel. Galvanic anodes are embedded in patch repairs to provide cathodic protection to the reinforcing steel immediately adjacent to the repair area. They will prevent secondary corrosion to the steel, commonly referred to as the 'Incipient Anode' or 'Ring Effect'. Figure 2 shows the cut section details on the zinc cake and the surrounding cementitious matrix.
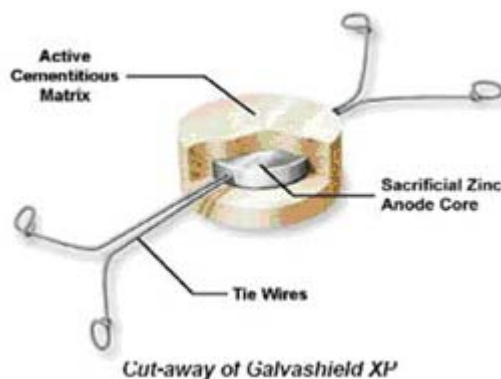
Figure 2. Cross section of galvanic anode used in the experiment

The sacrificial anode used in the experiments is Galvashield XP, marketed by M/s. Fosroc Chemicals (I) Pvt. Ltd. Galvashield XP is a sacrificial metal surrounded by a highly alkaline cementitious mortar, which has a pore solution pH sufficiently high for corrosion of the anode to occur and for passive film formation on the anode to be avoided as described in patent number WO94/29486PCT.

Because of its simplicity in installation, the sacrificial anodes both in the case of initial stage of construction as well as during the repair/rehabilitation after a few years during the maintenance of the structural members perform well in corrosion protection of the reinforced concrete members. Figure 3 shows the simplicity in the installation of a sacrificial galvanic anode.

Figure 3. Typical installation of galvanic anode at site

2.6 Steel density ratio
The number and spacing of anodes is determined by the steel density ratio. The ratio is a calculation of the surface area of the reinforcing steel to the area of repair. Product manufacturers supply the spacing tables based on the steel density ratio for each anode type. Anodes are estimated to provide 5 to 15 years of corrosion protection. The protective current

supplied by sacrificial anodes will decrease slowly with time as zinc corrosion products accumulate. The recommended anode spacing provided by the manufacturers provides a balance between desired service life and reasonable cost. Altering the anode spacing will change the service life, but the relationship between the spacing and the service life is not linear. Doubling the anode spacing (therefore halving the anode cost) will reduce the expected service life by much more than half. Halving the anode spacing will extend the expected service life by more than double, but at greatly increased cost. The steel density ratio is defined as:

$$\text{Steel density ratio} = \frac{(\pi) \, (\text{bar diameter})}{(\text{bar spacing})} \quad \ldots\ldots\ldots\ldots \quad (3)$$

3. IMPRESSED CURRENT TECHNIQUE

Corrosion of steel in concrete is a slow process. Due to the protective nature of concrete, it takes a reasonably long time for initiation and progress of reinforcement corrosion even in the case of severe corrosive exposure conditions. It is difficult to achieve a significant degree of reinforcement corrosion in a limited duration available for performing research studies.

The corrosion of reinforcing steel is generally accelerated by means of the impressed current technique. This is carried out to induce a significant degree of corrosion of reinforcing bars embedded in concrete in limited available time. The impressed current technique has been frequently used to study the effect of reinforcement corrosion on the cracking of concrete cover, bond behavior, and load-bearing capacity of reinforced concrete structural members.

The impressed current technique of corrosion acceleration has many advantages, in addition to the obvious savings in time and money. One advantage over other accelerated techniques is the ability to control the rate of corrosion, which usually varies due to changes in the resistivity, oxygen concentration, and temperature. Any change in one of the variables would be compensated for.

The impressed current technique, also called the galvanostatic method, consists of applying a constant current from a DC source to the steel embedded in concrete to induce significant corrosion in a short period of time. After applying the current for a given duration, the degree of induced corrosion can be determined theoretically using Faraday's law, or the percentage of actual amount of steel lost in corrosion can be calculated with the help of a gravimetric test conducted on the extracted bars after subjecting them to accelerated corrosion. Using the actual amount of steel lost in corrosion, an equivalent corrosion current density can be determined. The typical set up of the test arrangement for the impressed current technique is shown in Figure 4.
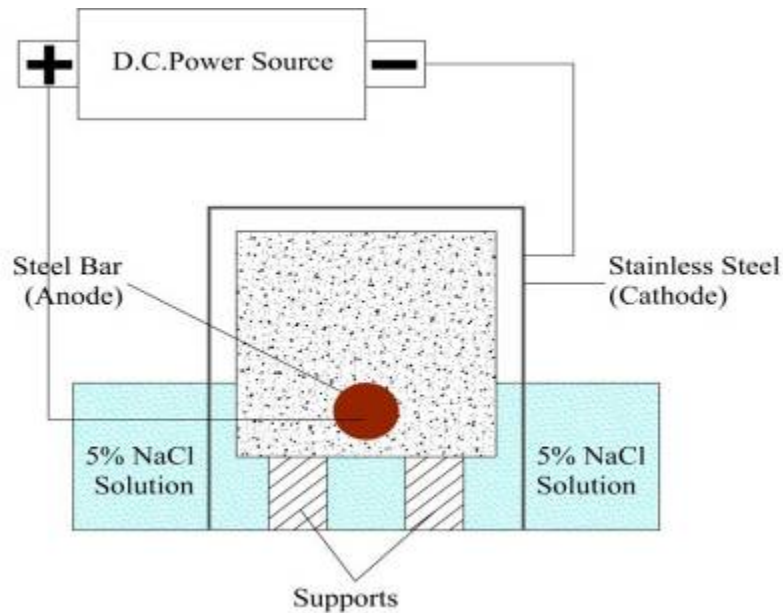
Figure 4. Typical arrangement for the impressed current technique

3.1. Calculation of degree of induced corrosion and equivalent corrosion current density
The mass of rust produced per unit surface area of the bar due to applied current over a given time can be determined theoretically using the following expression based on Faraday's law:

$$M^{th} = \frac{W \times I.app. \times T}{F} \qquad \ldots\ldots\ldots \qquad (4)$$

where

M^{th} = theoretical mass of rust per unit surface area of the bar (g/cm^2)

W = equivalent weight of steel which is taken as the ratio of atomic weight of iron to the valency of iron (27.925 g)

I.app. = applied current density (Amp/cm^2)

T = duration of induced corrosion (sec) and

F = Faraday's constant (96487 Amp-sec).

The actual mass of rust per unit surface area may be determined by gravimetric test in accordance with ASTM G1 (12) on rebars extracted from the concrete by breaking the specimens after the accelerated corrosion test is completed:

$$M_{ac} = \frac{(W_i - W_f)}{\pi DL} \qquad \ldots\ldots\ldots\ldots\ldots \qquad (5)$$

where

M_{ac} = actual mass of rust per unit surface area of the bar (g/cm^2)

W_i = initial weight of the bar before corrosion (g)

W_f = weight of the bar after corrosion (g) for a given duration of induced corrosion (T)
D = diameter of the rebar (mm) and
L = length of the rebar sample (mm).

The degree of induced corrosion is also expressed in terms of the percentage weight loss (ρ) calculated as

$$\rho = \frac{W_i - W_f}{W_i} \times 100 \qquad \text{------------------} \qquad (6)$$

4. TEST SPECIMENS AND EXPERIMENTAL PROGRAM

Based on the extensive literature survey conducted, it was decided to study the performance of sacrificial anodes in concrete specimens using the impressed current technique. The performance of the sacrificial anode was compared with the control specimens. It was also decided to study the effect of preconditioning of the sacrificial anodes on their performance in resisting corrosion.

4.1 Test specimen
Three types of specimens have been used for the accelerated corrosion test. The test specimens consisted of concrete prisms in which a single 25mm diameter ribbed bar was embedded in the centre. Figure 5 shows the details of positioning the galvanic anodes and preparation of the specimen. The dimensions of the concrete prisms are 100mm x 100mm x 500mm. The moulds were constructed with steel with the required tolerance limits as per the Indian Codes. Cubes of 150mm x 150mm x 150mm were also cast to evaluate the compressive strength of concrete. The rebars in two of the specimens were protected using the self regulating sacrificial anodes while one specimen was cast as a control without any protection. In one of the specimen, the self regulating sacrificial anode was tied to the rebar in a dry state, i.e without soaking in water. In the other specimen, the self regulating sacrificial anode was tied to the rebar after soaking in water for a period of about 15 minutes.
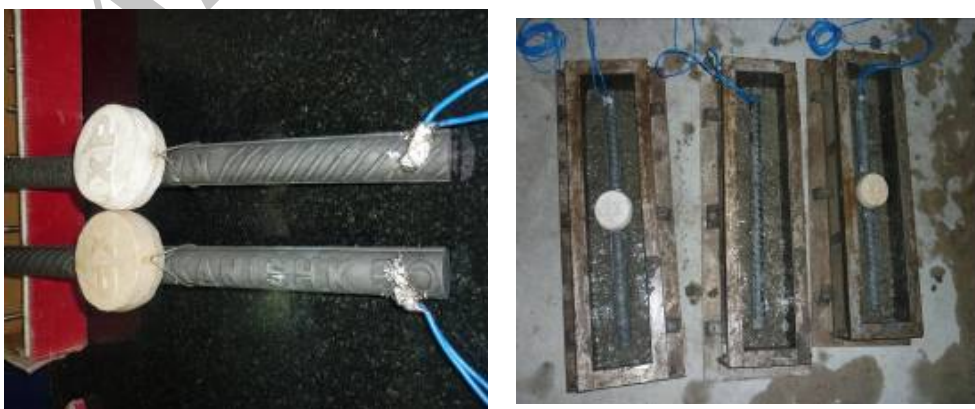

Figure 5. View of the specimen preparation

4.2 Materials and mixture proportion

The constituent materials consisted of OPC cement, 20mm & 12mm coarse aggregate, river sand and potable water. The concrete mix was designed for a characteristic strength of 20 MPa. Table 1 gives the mixture proportion of concrete. Table 2 gives the compressive strength of the concrete cube specimen. 25mm diameter reinforcing bars were used in the study. The yield and tensile strength of the bars were 554.7 MPa and 687.8 MPa respectively.

Table 1: Details of the concrete mix design

Mix designation	M20
Cement (kg/m^3)	300
Water cement ratio	0.55
River sand (kg/m^3)	739.92
20 mm (kg/m^3)	703.70
12 mm(kg/m^3)	487.14
Free water (kg/m^3)	165

Table 2: Details of the compressive strength test results

Age in days	Average compressive strength in MPa
03 Days	8.25
07 Days	16.75
28 Days	24.75

4.3 Mixing, casting and curing

A pan type concrete mixer was used for mixing the materials during the preparation of the test specimens. Before placing the concrete, the weight of the reinforcement for each specimen was recorded and the bars were aligned at the centre of the prism moulds with the required cover of about 25mm. A mold-releasing chemical was applied to the inside surface of prisms and to the cube moulds. A table vibrator was used for compaction of both beam specimens and cube specimen. At the end of casting, polyethylene sheets were used to cover the samples for the next 24 hours and later the specimens were water cured. Figure 6 shows the soaking of anode in water for preconditioning and the finished prisms.

Figure 6. Specimen precoonditioning & concreted with required wires

4.4 Current-induced corrosion process

Figure 7 shows the typical arrangement of the current – induced accelerated corrosion setup for concrete specimens. The magnitude of corrosion was measured using percentage of weight loss. A method developed for inducing corrosion by externally applied electric current was used in this study. An electric current is passed from the power source to the reinforcing bar embedded in concrete and the stainless steel plate immersed in 5% NaCl solution. This stainless steel plate acts as a cathodic site, which consumes the electrons given out by the corroding deformed bar. Generally, 0.5 mm/year is the rate at which corrosion of the rebar takes place in RC structural elements. Since the present study involves accelerating the corrosion of the rebar through impressed current, the focus was to achieve maximum corrosion level in the shortest possible time and to evaluate weight and diameter loss in the rebars.

Figure 7. Typical vew of accelarated corrosion setup

A power supply with an output of 10 V DC was used to induce the corrosion. The positive terminal was connected to the rebar and the negative terminal was connected to the stainless steel plate. This set up has worked well, which was confirmed by the presence of corrosion along the bar when specimens were checked for loss in diameter. After the power supply was turned on, the current flowing thought the system was recorded at 1 hour interval using a computer controlled data acquisition system.

4.5 Measurement of half cell potential reading

Periodically half cell potential readings were taken every day. Before taking the half cell potential readings, the direct current supply to the test specimen was put off at least an hour in advance. This method covers the estimation of electrical half cell potential of reinforcing steel in concrete for the purpose of determining the corrosion activity of the reinforcing steel. A copper-copper sulphate (Cu-CuSo4) electrode (reference electrode) was used to measure the half cell potential. It consists of a rigid tube that is non reactive with copper or copper sulphate, a porous sponge placed at the conduct end that remains wet by capillary reaction and a copper rod that is immersed within the tube in a saturated solution of copper sulphate. The solution was prepared with reagent grade copper sulphate crystals dissolved in distilled water. The solution was considered super saturated when an excess of crystal (undissolved) lies at the bottom of the solution.

Half-cell potentiometer works on the principle of measuring voltage in the circuit of reinforcement and cover concrete using Copper Sulphate Half-Cell. This method essentially consists of measurement of the absolute potential of the concrete with reference to the reference electrode. The reference guidelines for the probability of corrosion as given in ASTM C-876 (11) is presented in the Table 3. Figure 8 shows the level of corrosion and the cracks noticed on the specimen.

Figure 8. Typical view of corrded specimen

Table 3: Reference guidelines for probability of corrosion (ASTM C-876)

Sl. No	Measured potential difference	Probability for corrosion
1	More negative than (-) 350 mV	High probability of corrosion
2	Between (-) 200 mV to (-) 350 mV	Uncertainty of corrosion
3	More positive than (-) 200 mV	High probability of no corrosion

The half cell potential measurements were conducted on the top portion of the specimens. It is a pre requisite that the structural elements that are to be subjected to half cell measurements have to be fully saturated during the measurements and hence the specimens were pre wetted before taking the readings. Even though this method has limitations, it is still widely used and is being recognized to be a useful tool for assessing the probability of corrosion. The half cell potential readings gives an indication for the probability of the corrosion and the values were used to conclude the time of termination of the direct current to the specimens.

In the present study, when the half cell values reached a value of around -600 mV, the test was stopped. The half cell values were used for determining the period of application of the impressed current as well as to determine the time at which the test has to be terminated. Figure 8 shows the typical view of the corroded specimen in which the half cell potential readings were taken regularly.

5. EFFECT OF IMPRESSED CURRENT ON THE PERFORMANCE OF SELF REGULATING ANODES

Figure 9 shows the Current Vs Time for the controlled specimen and specimen installed with self regulating anodes, which are conditioned and unconditioned respectively. It is seen from the figure that the corrosion initiation time has been enhanced for the specimen installed with conditioned self regulating anode. The corrosion initiation time for the controlled specimen was observed at 9 days. In the case of the specimen installed with unconditioned self regulating anode, corrosion initiation was observed at 90 days, which is about 10 times of the control specimen. However the corrosion initiation time for the specimen installed with conditioned self regulating anode was observed beyond 100 days. .
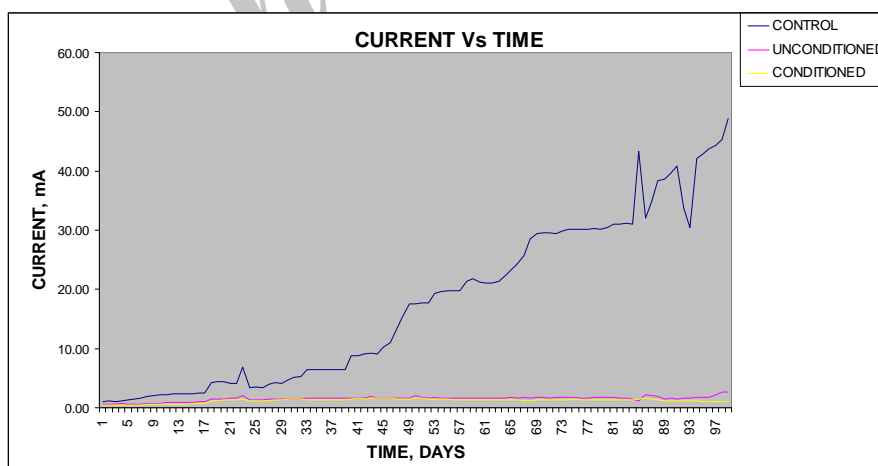

Figure 9. Current VS. time – different sepcimen

Figure 10 shows clearly that the performance of the specimens keeping conditioned specimen as datum, specimens provided with self regulating sacrificial galvanic anodes was

much better compared to the control specimen and improvement to the tune of about 100% was noticed in the conditioned one, while in the case of unconditioned one, the improvement was 60% over the control specimen.
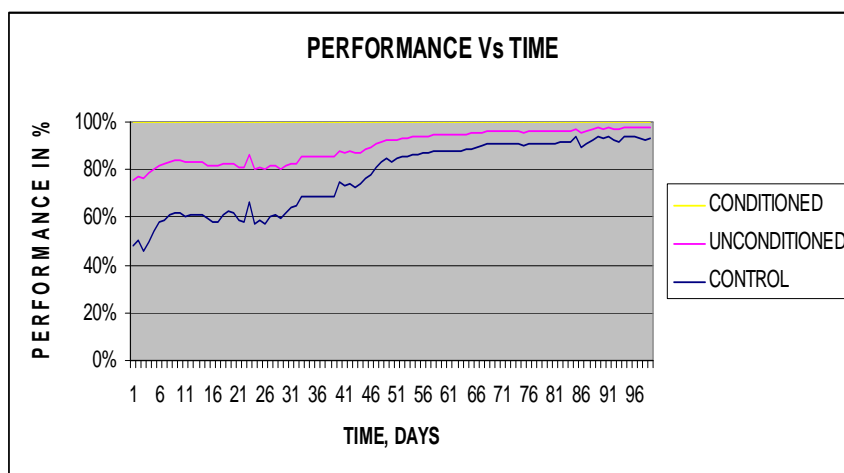

Figure 10. Performance of coonditioning of anodes VS. control

6. MEASUREMENT OF WEIGHT LOSS IN REBARS

After the half cell potential readings reached values of about–600mV, the test was terminated and the corroded specimens were broken to remove the rebars embedded in to the concrete specimen. The bars were cleaned as per ASTM G 1-03 standards "Preparing, cleaning and evaluating corrosion test specimens" (12) and the cleaned bar was weighed and the total percentage loss in weight was determined. Figure 11 shows the cleaning of the corroded specimen and also the reduction in the cross sectional of the bar.

Figure 11. Typical view of cleaned rebar and view of reduced cross section

7. TEST RESULTS

The test results exhibited a clear difference on the rate of corrosion by means of the loss in diameter and also weight loss. As mentioned earlier, the original diameters of the rebars were 24.54mm, 24.56 & 24.56 for the control, specimen with dry anode and the specimen with soaked anode respectively. This was calculated taking in to account density of the steel and the length of the rebar placed in the specimen and as follows:

$$\text{Diameter} = \frac{\sqrt{(1.602 \times \text{Weight of rebar in kg})}}{\text{Length in meter}}$$

Similarly the weight of the rebar in the control specimen, specimen with dry anode and the specimen with soaked anode were 1.691kg, 1.695kg & 1.695kg respectively and the length of the rebar was 450mm.

After the accelerated corrosion test, the weight of the rebar in the control specimen reduced to 1.155kg and the reduction was 0.536kg. This works out to a weight loss of 31.7%.

The weight of the rebar in the specimen with dry anode after the accelerated corrosion reduced to 1.440kg and the reduction was 0.255kg. This works out to a weight loss of 15.04 %. The results are tabulated in Table 4.

After the accelerated corrosion test, the weight of the rebar in the specimen with conditioned anode reduced to 1.525kg and the reduction was 0.170kg. This works out to a weight loss of 10.03%. Figure 12 shows the test results in terms of weight of the individual specimen after the cleaning and weighing. The figure also illustrates the pitting corrosion that has taken place.
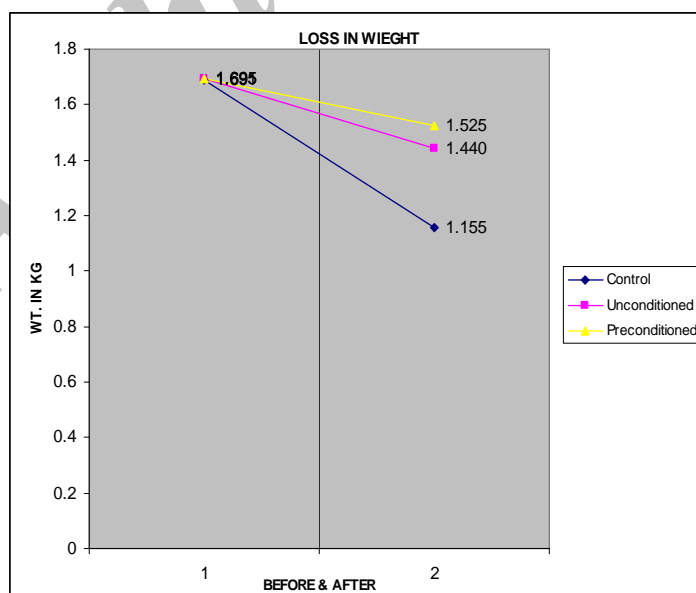

Figure 12. Weight of individualspecimen before and after corrosion

Table 4. Details of initail, final weight and percetgae of loss

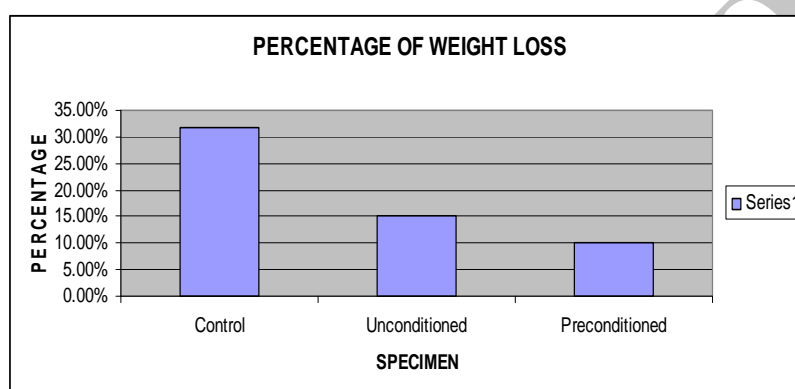| Sl. No.	Specimen	Weight of the rebar in kg	Weight of the rebar after impressed current	Percent loss in weight
1	Control	1.691	1.155	31.70%
2	Unconditioned	1.695	1.440	15.04%
3	Preconditioned	1.695	1.525	10.03%

Figure 13. Weight loss in percentage

Figure 14. Test result in terms of weight

8. DISCUSSIONS OF ANALYSIS OF RESULTS

The rate of corrosion for the specimens provided with sacrificial galvanic anodes is lower when compared to the control specimen. It was also noted that there exists a difference between the specimens which were soaked in water before installation and the one that was installed in a dry condition. The corrosion resistance of the specimen installed with the sacrificial anodes soaked in water was better as compared to the dry one. Figures 13 and 14

show the percentage of loss and the weight loss, respectively.

After corrosion initiation, its progression formed additional corrosion products resulting in increased volume compared to the non corroded metal. Longitudinal corrosion cracks are formed along the corroding reinforcing bar when the tensile stress in the concrete surrounding the reinforcing bar exceeds the tensile strength of the concrete.

The cracking ultimately results in the delamination and spalling of the concrete. This exposes the reinforcement directly to the NaCl solution and corrosion is further accelerated. Moreover, the bond between steel and concrete is reduced. Pitting corrosion results in the reinforcing bar by introducing notches on the surface of the steel bars that leads to a premature necking.

In the case of the anode without precondition, the pores on the precast mortar matrix saturated with lithium hydroxide (LiOH), will absorb water from the repair mortar. Hence, there is a depletion of water in the repair mortar, leading to improper hydration and strength development leading to a weaker transition zone. If the anode is preconditioned, the above situation will be prevented as the saturated anode will not absorb the water/cement slurry from the repair mortar

The other positive influence of preconditioning could be attributed to the fact that the conditioned anode will allow the water to be absorbed by the surrounding repair mortar, thereby maintaining the pores in the matrix, which is saturated with lithium hydroxide. In case the anode is dry, then it will absorb the water from the surrounding repair mortar and the pores in the anode will be blocked and there is no room for the zinc oxide to get deposited in the pores. Hence the zinc oxide that is formed exerts a tensile force on the concrete thereby cracking the cover concrete and leading to reduced performance level of the anodes in resisting corrosion of rebars.

In the present study, cracking occurred much earlier in the case of the specimen with unconditioned anode compared to the one soaked in water. The cracking of the specimen resulted in further ingress of chlorides as the specimens were immersed in a 5 % solution of Nacl for the impressed current test. This led to the widening of the cracks and resulting in higher rate of rebar corrosion. At the same time, the performance of the specimen with unconditioned anode was better compared to control specimen. The study clearly reveals the fact that self regulating anodes with proper preconditioning will have a large bearing on the corrosion resistance of concrete. This procedure of soaking the anodes in the clean water before installation is being advised by the manufacturer and also reported in the technical data sheet.

9. CONCLUSION

The provision of self sacrificial zinc anodes improved the corrosion resistance of concrete compared to the control concrete and stable current output for cathodic protection of the steel reinforcement. The present investigations goes to prove that in situations, where durability is of prime concern, particularly in marine environment where chlorides are found in abundance, the use of self regulating anodes will be beneficial to Reinforced concrete structures as they show increased resistance to chloride ion diffusion. It is possible to enhance the corrosion resistance

of Reinforced concrete structural elements through the installation of Self regulating anodes, which are pre conditioned through soaking in water.

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