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PERFORMANCE OF THE SACRIFICIAL GALVANIC ANODES IN REHABILITATION OF MARINE STRUCTURE AT PORT BLAIR, ANDAMAN AND NICHOBAR ISLANDS, INDIA

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ABSTRACT

In recent years, more and more focus has been shifting towards repair and rehabilitation of deficient concrete infrastructures rather than replacement, either in full or replacing the structural members. While carrying out the rehabilitation, one should keep in mind that the methodology should have cost effective strategy and durability. The deterioration caused by the corrosion of reinforcing steel in concrete structures has been recognized as one of the greatest maintenance challenges being faced by many government agencies and other private owners including the engineering contracting companies in the filed of construction industry today. Technological advances have created a wide range of new product and systems which claim to provide long-lasting protection and serviceability for these structures. However, in order to effectively address the problem it is essential to first understand the cause of the corrosion. The paper describes in detail the philosophy of the corrosion and to evaluate the effect of having anodes installed in the concrete members. The paper also describes in detail investigations conducted on a corrosion damaged jetty approach portion, the repair methodology suggested for the rehabilitation of the structure and executed. The repair methodology proposed included the provision of galvanic anodes. The data presented on the monitoring of the repaired jetty through half cell potential test conducted over a period of one year from the time of completion of the repair to assess the effectiveness of the sacrificial anodes. The investigations have clearly demonstrated that galvanic anodes have proved to be an effective corrosion control technique for reinforced concrete structures.

Keywords: concrete structures, corrosion, galvanic anodes, half cell potential, rehabilitation, marine.

1. INTRODUCTION

Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, especially of the structures located in the coastal marine environment leading to the failure of the structures [1].

As a result, the repair costs nowadays constitute a major part of the current spending on existing infrastructure. Quality control, maintenance and planning for the restoration of these structures need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage. Corrosion loss consumes considerable portion of the budget of the country by way of either restoration measures or reconstruction. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could effect lot of saving. Moreover, the repair operation themselves are quite complex and require special treatments of the cracked zone, and in most instances the life expectancy of the repair is limited. [2-5]. In such conditions, the corrosion protection methodology is not addressed properly, the cracks reappear and resulting in again breaking and redoing the entire process like cleaning the rebar, applying epoxy based jointing compound, providing form work, providing micro concrete or polymer modified mortar and so on…followed by some protective coating.

This paper explains in detail about the usage of sacrificial anodes, which postpones the corrosion to a maximum and a case study on the marine structures rehabilitated using the sacrificial anodes at highly corrosive environmental zone Andaman and Nichobar Islands, India.

2. CORROSION

Corrosion within concrete structures is commonly caused by either the presence of sufficient concentrations of chloride ions or carbonation. The most important causes of corrosion initiation of reinforcing steel are the ingress of chloride ions and carbon dioxide to the steel surface.

After initiation of the corrosion process, the corrosion products (iron oxides and hydroxides) are usually deposited in the restricted space in the concrete around the steel. Their formation within this restricted space sets up expansive stresses, which crack and spall the concrete cover. This in turn results in progressive deterioration of the concrete.

Figure-1 shows the typical result of the cracking due to the expansive stresses on account of the corrosion.

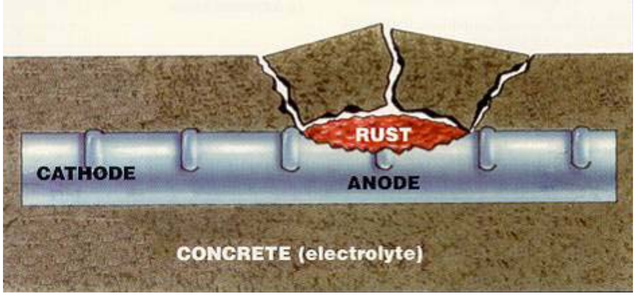


Figure-1. Expansive stresses resulting in cracking.

2.1 Corrosion mechanism

Corrosion of steel is an electrochemical process that involves the progressive removal of atoms of iron (Fe) from the steel being corroded and embedded in concrete. The reaction of FE $^{++}$ ions with the OH $^{-}$ ions and dissolved O_2 molecules causes rust which results into cracking of cover and further deterioration of concrete. Rust is a chemical by-product of the corrosion process, and it often accumulates at places other than where the actual corrosion of metal iron occurs. A simplified schematic diagram illustrating breaking of the passivating layer due to carbonation and chloride is shown in Figures 2 and 3, respectively.

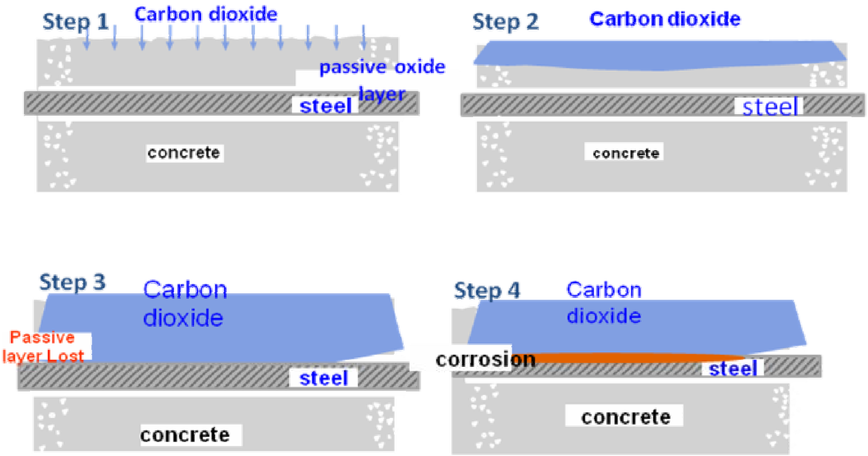


Figure-2. Typical view of carbonation corrosion.

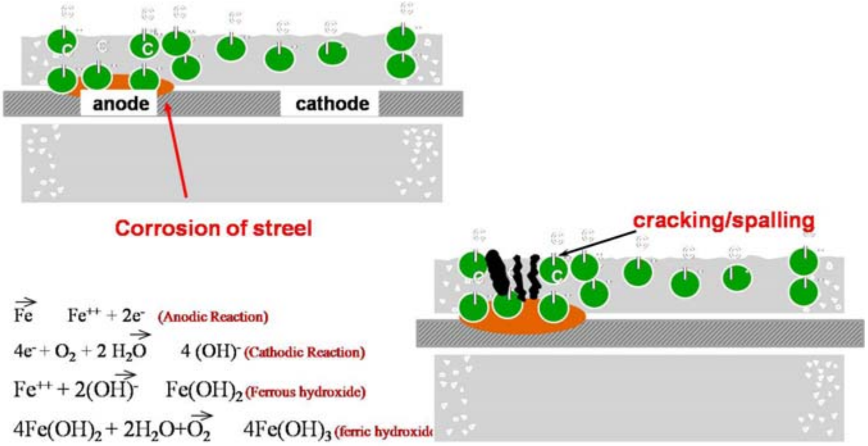


Figure-3. Typical view of chloride corrosion.

2.2 Ring anode corrosion

While early damage is often not a serious structural concern, corrosion acts like a disease, normally compared to cancer and must therefore be treated before it become a significant problem. In many cases, a "chip and patch" approach to concrete repair is adopted. This procedure entails removal of the damaged concrete, cleaning the reinforcing steel, and patching the repair area with micro concrete or a polymer modified mortar, either with or without any coating to the rebars. Repairs of this nature will in many situations actually accentuate corrosion in the reinforcing steel adjacent to the repair area. This phenomenon is often referred to as "Ring Anode", or "Patch Accelerated" corrosion.

Ring anode corrosion results from electrochemical incompatibilities between the repair and the substrate concrete. Differences between the base concrete and the repair can create electrical potentials, which drive new corrosion cells across the interface between the patch and the substrate.

Factors which can lead to corrosion problems include differences in chloride ion content, pH, permeability of even different types of reinforcing steel which are coupled together. These factors may lead to accelerated corrosion in the repair itself, but more often results in deterioration of the concrete adjacent to the repair.

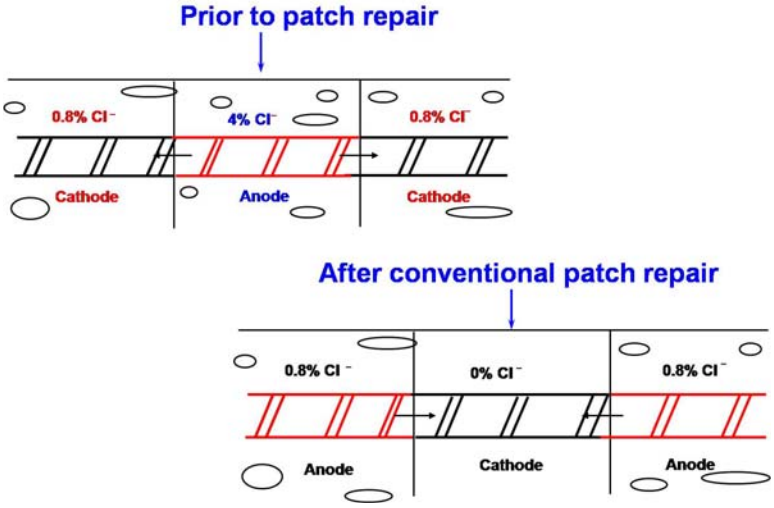


Figure-4. Ring anode corrosion adjacent to a patch repair

The rate of deterioration due to ring anode corrosion is dependent upon the same factors which control the overall rate of corrosion. These include the amount and difference in chloride content, moisture availability, temperature, and permeability of the concrete. Figure-4 illustrates corrosion adjacent to a patch repair due to the ring anode effect.

- Corrosion occurs due to break down of passivation film.
- If passivation film breaks down due to reduction in pH - Corrosion by carbonation.
- If passivation film breaks down due to chloride ions - Corrosion by chloride attack.
- Once corrosion is initiated, corrosion cell created and rust occurs at anode.
- Since volume of rust is several times greater than steel, expansive force builds up in concrete resulting in cracking and spalling.

3. EMBEDDED GALVANIC ANODES

Embedded galvanic anodes are galvanic devices designed to neutralize or slow down new corrosion cells, which would otherwise develop around a patch, there by extending the services life of the repair. These discrete units are designed to be attached to the rebar and incorporated within the patch repair. Based upon many of the same principles used for protecting pipelines and ships from corrosion, these anodes are “sacrificial” in nature. The anodes take advantage of the natural galvanic differences which exist between different metals.

The heart of the devices is a metallic anode composed of zinc, which is cast around a pair of steel tie wires. This unit is encased within a cementitious shell. The device is shaped like a short cylinder, about 2.5 inches in diameter, and 1 inch thick. The tie wires extend out opposing sides of the anode to enable it to be tied to the reinforcing steel. Figure-5 shows the typical view of different galvanic anodes being used in the repair 7 rehabilitation of rc structures. Figure-6 shows a cut-away view of a sacrificial galvanic anode.

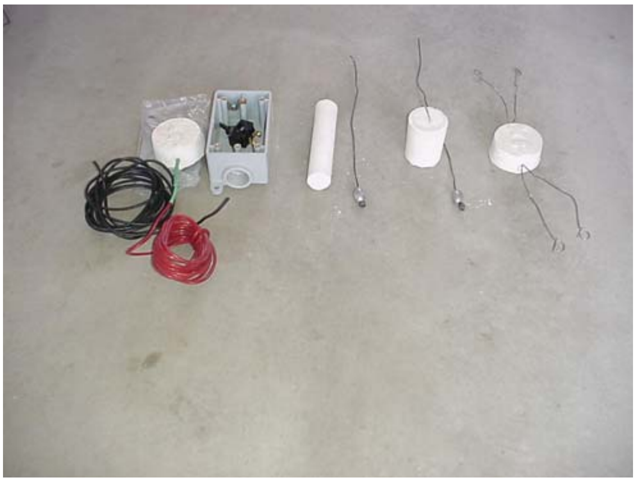


Figure-5. Typical view of the galvanic anodes and monitoring box.

Figure-6. Typical cut-away view of galvanic anode.

As the zinc corrodes, it releases a supply of electrons. This electrical current travels through the tie wires, into the surrounding reinforcing steel to reduce new corrosion activity on the steel. The output from the anode will vary according to a number of variable including concrete resistivity, moisture content, temperature, and reinforcing steel density. In the same way that climatic variations will affect the degree of corrosion in an unprotected structure, the environment into which the anode is installed will have a large influence on its current output. In humid and/or warm climates the anodes tend to corrode more aggressively than in cool and/or dry regions. There, fluctuations in the current output of the anode will vary with changes in the corrosion activity of the steel. The conditions that exist within the concrete will also influence the output of the anode. The permeability, chloride content, pH, conductivity, and steel density within the concrete will all affect the anode current output. The more severe the situation, the more aggressive the corrosion will be if anodes are not installed. By embedding galvanic anodes within the repair, the anodes provide galvanic protection, thereby reducing the tendency for the steel in the adjacent area to corrode.

Galvanic 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 namely.

a) Zinc has high corrosion efficiency i.e., higher percentages of electrons are discharged from the zinc as it corrodes. These electrons 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 into the concrete structure.
c) Zinc anodes are suitable for use in 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.

4. DESCRIPTION OF STRUCTURE

The main components of the approach portion of the referred Fisheries jetty approach situated at Port Blair, Andaman and Nichobar Islands are as follows:

a) The Fisheries jetty approach was built on 78 numbers of precast driven piles consisting three rows
b) The pile size are 400mm x 400mm
c) The spacing between rows pile and in between two piles was observed as 3.0m
d) The following are the beam sizes on the Fisheries jetty approach:

Longitudinal beams	350 mm x 400 mm (excluding deck slab)
Transverse beams	350 mm x 400 mm (excluding deck slab)
Slab thickness	250 mm without wearing coat

The cast driven piles head were broken after the complete driving and the rebars were exposed. With these rebars the reinforcement of the longitudinal and cross beams were provided as per the detailing followed by in-situ concreting of beams and deck slab were done as reported.

Figure-7 shows the layout of Fisheries jetty approach portion. Figure-8 shows the over all view of the Fisheries jetty approach portion before rehabilitation.

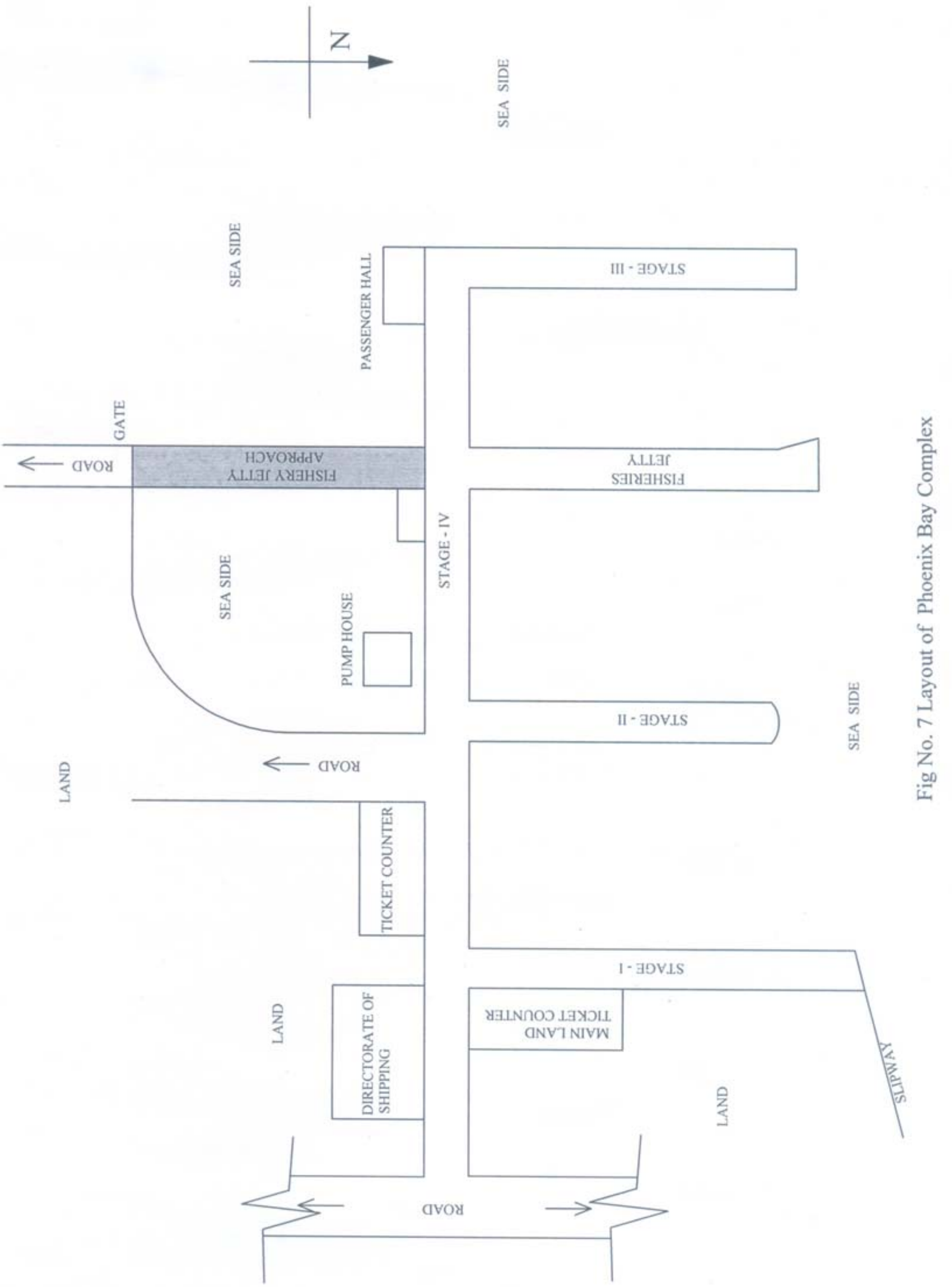


Figure-7. Layout of Fisheries jetty approach portion.

Figure-8. A view of the corrosion affected fisheries jetty approach.

Figure-9. Typical view of the corroded/spalled beam.

5. INVESTIGATIONS TO ASSESS THE CORROSION DAMAGE OF THE FISHERIES JETTY APPROACH

The following tests were conducted to assess the quality of concrete and extent of corrosion in the various structural elements of the Fisheries jetty approach:

a) Half cell potential test
b) Carbonation Test
c) Chloride Test

The following structural elements were investigated:

a) Piles
b) Beams

A brief description of the test methods employed is discussed below.

5.1. Half-Cell electrical potential method

5.1.1. Principle

Half-cell potential measurements involve measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. The half-cell is usually a copper/copper sulphate or silver/silver chloride cell. The concrete functions as an electrolyte and the risk of corrosion of the reinforcement in the immediate region of the test location may be related empirically to the measured potential difference. ASTM C876 - 09 [6] gives a Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete.

The case study presented in this paper, the half cell used was copper/copper sulphate.

5.1.2 Half-Cell potential test apparatus

The half cell testing apparatus consists of the following:

Half-cell

The cell consists of a rigid tube or container composed of dielectric material that is non-reactive with copper or copper sulphate, a porous wooden or plastic plug that remains wet by capillary action, and a copper rod that is immersed within the tube in a saturated solution of copper sulphate. The solution is prepared using reagent grade copper sulphate dissolved to saturation in distilled or deionized water.

The rigid tube should have an inside diameter of not less than 25 mm; the diameter of the porous tube should not be less than 13 mm; the diameter of the immersed copper rod should not be less than 6 mm and its length should be at least 50 mm. Present criteria based on the half-cell reaction of $Cu \rightarrow Cu^{++} + 2e$ indicate that the potential of the saturated copper-copper sulphate half-cell as referenced to the hydrogen electrode is -0.316 V at 72°F (22.2°C). The cell has a temperature coefficient of about 0.0005V more negative per oF for the temperature range from 32 to 120°F (0 to 49°C).

Electrical junction device

An electrical junction device is used to provide a low electrical resistance liquid bridge between the surface of the concrete and the half-cell. It consists of a sponge or several sponges pre-wetted with a low electrical resistance contact solution. The sponge can be folded around and attached to the tip of the half-cell so that it provides electrical continuity between the porous plug and the concrete member.

Voltmeter

The battery operated voltmeter with ± 3% end of scale accuracy at the voltage ranges in use. The divisions on the scale used should be such that a potential of 0.02 V or less can be read without interpolation.

Electrical lead wires

The electrical lead wire should be such that its electrical resistance for the length used does not disturb the electrical circuit by more than 0.0001 V. This has been accomplished by using no more than a total of 150 m and the wire should be suitably coated with direct burial type of insulation.

5.1.3. General test procedure

Measurements are made in either a grid or random pattern. The spacing between measurements is generally chosen such that adjacent readings are less than 150 mV with the minimum spacing. A direct electrical connection is made to the reinforcing steel with a compression clamp or by brazing or welding a protruding rod. To get a low electrical resistance connection, the rod should be scraped or brushed before connecting it to the reinforcing bar.

The bar is connected to the positive terminal of the voltmeter. One end of the lead wire is connected to the half-cell and the other end to the negative terminal of the voltmeter. Under some circumstances the concrete surface has to be pre-wetted with a wetting agent. The electrical half-cell potentials are recorded to the nearest 0.01 V [7].
The half cell potential survey was conducted on the piles and beams before taking up the repair work. The reference

guidelines for the probability of corrosion ASTM C-876 [6] is presented in the Table-1.

Table-1. Reference guidelines for probability of corrosion (ASTM C-876).

S. 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 pre determined grid locations marked on the structural elements of the Fisheries jetty approach. In the piles and beams, grids of approximately 250 mm x 100 mm were marked on those locations. 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 piles and beams were pre wetted before taking the readings. Figure-10 shows the half cell potential test in progress on the pile.

Figure-10. A view of the half cell potential test in progress on the pile before rehabilitation.

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.

5.2 Carbonation test on concrete core samples

When any concrete structure is exposed to atmosphere, the surface of concrete comes in contact with Carbon-di-oxide present in the atmosphere. The calcium present in the cement/concrete will react with the Carbon-di-oxide forming calcium carbonate resulting in reduction of alkalinity in concrete. Whenever, the concrete is dense and impervious to atmospheric agents, the carbonation will be restricted to surface only. However, if the concrete is pervious, the carbonation reaction continues inwards and reaches the concrete surrounding the rebars, thus reducing the alkalinity of concrete and causing initiation of corrosion.

Carbonation test was conducted immediately on all the core samples that were extracted from the RC members. The test was conducted using phenolphthalein indicator in dilute alcohol. The uncarbonated portion will turn pink, while the carbonated portion remains colourless. The measured depth of change in colour or otherwise will indicate the carbonated level of concrete. The depth of carbonation levels are tabulated in the Table-2.

Table-2. Results of the carbonation test on the concrete core samples.

S. No.	Member	**Depth of carbonation** (mm)	Stipulation
1	Column C5	35	Carbonation should not reach reinforcement level during the life time of the structure.
2	Column C 16	30	
3	Beam B1	30	
4	Beam B18	25	
5	Slab C1C2 - C4C5	15	

5.3 Chloride determination test

Chloride determination test was carried out on concrete powder samples that were extracted from the tested cores. The presence of higher amount of chlorides in concrete surrounding the reinforcement will result in corrosion of rebars. The quantity of chlorides in concrete is determined by chemical analysis and is expressed in terms of weight of concrete. The chloride levels are tabulated in the Table-3.

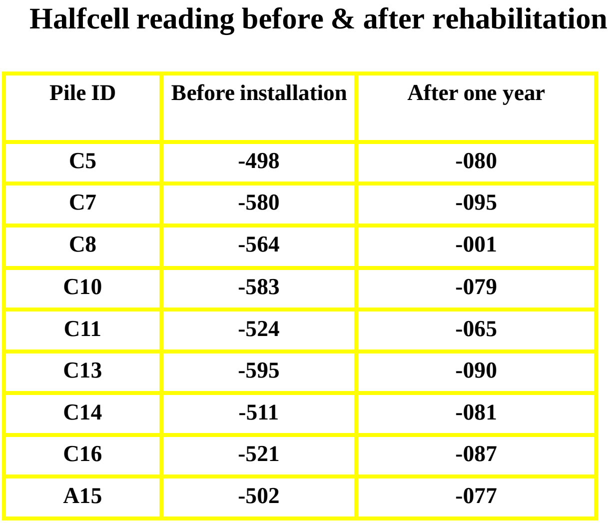
Table-3. Results of chloride samples.

S. No.	Member identification	Chloride content (Kg/m^3)	Stipulation
1	Fisheries jetty approach-approach - column	0.82	Max. Chloride content in concrete shall not exceed 0.025% (i.e., 0.6 kg/cum of concrete) as per IS: 456-2000 by weight of concrete.
2	Fisheries jetty approach-approach - beam	0.81	
3	Fisheries jetty approach-approach - slab	0.82	

5.4 Analysis of the test results

The half cell potential readings taken on the various structural elements, viz., piles and beams of the corrosion affected Fisheries jetty approach are given in the Table-4.

Table-4. Halfcell readings before 7 after 1 year of rehabilitation.



Halfcell reading before & after rehabilitation

Pile ID	Before installation	After one year
C5	-498	-080
C7	-580	-095
C8	-564	-001
C10	-583	-079
C11	-524	-065
C13	-595	-090
C14	-511	-081
C16	-521	-087
A15	-502	-077

It is seen from the Table-4 that most of the readings show a value which is greater than -350 mV. As per Table-1, readings greater than -350 mV indicate a high probability of corrosion. At a few locations, the readings are more than -595mV confirming the severity of the corrosion. The half cell potential measurements coupled with the visual survey clearly demonstrate that the structural elements of the Fisheries jetty approach require immediate rehabilitation. The half cell potential readings in the piles and beams indicate that there is a high probability of corrosion in these structures, except few beams where the values indicated were around -200mV indicating uncertainty of corrosion. The half cell potential values obtained during the investigations prove that the corrosion is active.

The carbonation test revealed that the concrete had carbonated to a depth of 15-35 mm (Table-2). However as the referred structure is a marine structure and the cover provided was 75mm, the carbonation has not reached the rebar level. It is seen from Table-3 that chloride contents are above 0.82 kg/m^3 for the test samples, which is much higher than the threshold value of 0.6kg/m^3 for reinforced concrete as specified by IS: 456:2000 [8].

Thus it is being concluded that the corrosion is essentially due to the ingress of chloride as the value of chloride levels are much more than the threshold limits.

6. REPAIR METHODOLOGY

Based on the analysis of the test results, a repair methodology was proposed to be adopted for the piles and beam. It was decided to take additional care for the corrosion problem by implementing some new technology and not only application of some protective coating to the rebar after removing the contaminated concrete.

A proper support system was designed and placed in position before taking up the repair and rehabilitation. After the support system was installed, the spalled/loose concrete were chipped from face of the piles.

All the spalled, cracked concrete and pre-applied mortars were removed by chipping to expose the reinforcing steel. The concrete was removed about 20mm behind the rebars. The repair sequence was so chosen that no two adjacent piles were chipped off at a time.

As the concrete was contaminated with chlorides, the chipped of surfaces of the concrete were repeatedly cleaned with potable water using high pressure water jet equipments during the low tide level. The exposed rebars were also cleaned with high pressure water jet and mechanical cleaning and also resorted to where ever required. The existing corroded rebars were coated with zinc based protective coating.

Since the repair methodology involved provision of a micro concrete jacket from the design point of view, shear connectors were provided at every 500mm c/c on the faces of piles and beams in a staggered manner. The shear connectors were anchored using polyester resin. The additional reinforcement was tied to the shear connectors so that the connectivity to the core concrete of the structure is ensured. The missing/heavily corroded ties were replaced.

The galvanic anode used was an amphoteric zinc block embedded within a specially formulated cementitious mortar having a pore solution pH which is 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 PCT/GB94/01224 was used in the rehabilitation of the structure.

Galvanic anode was positioned in such a way to ensure all round contact with the jacketed micro concrete and was attached to the existing/ additional reinforcement using the wire ties. Galvanic anode fixing tool was used to tighten the wire ties, so that no free movement was possible, thus ensuring electrical continuity. Figure-11 shows a view of the fixing of galvanic anode to the pile. In order to check the electrical continuity between wire ties and reinforcement bar, a voltmeter was used.

Figure-11. Typical position of galvanic anode and application of zinc rich primer.

The number of galvanic anode to be provided in the micro concrete jacketed portion was determined based on the quantity of the steel provided in the micro concrete jacketed portion and as per the manufacturer's specification one number of galvanic anode per square meter surface area of the micro concrete. The connectivity was checked before and after installation of the galvanic anodes. Leads were taken from the steel and also from the sacrificial anodes to the junction boxes which were fixed on the surface of the micro concrete, so that the readings could be taken as and when required to monitor the corrosion potentials over a period of time to evaluate the efficiency of the Galvanic anode. Figure-12 shows a closer view of the corrosion monitoring box to be fixed on the surface of the jacketed portion for monitoring half cell potential readings over a period of time.

Figure-12. A view of corrosion monitoring box.

The form work for the required size and shape was fabricated using waterproof ply wood of sufficient thick so that the form work does not bulge or undergo deformation while pouring the micro concrete. A two component epoxy resin jointing compound was applied on the surfaces of the piles and beams. This was especially recommended as the chloride ions had already ingressed into the core concrete and the resin jointing would act as a barrier against the ingress of chloride ion from the core concrete to the newly laid micro concrete. The jointing compound would also ensure proper bond between the core concrete and the jacketed micro concrete.

The members below water level were jacketed with under water anti wash and non shrink micro concrete of M45 grade. Above the high tide level, non-shrink free flow micro concrete of M45 grade was used. The micro concrete consisted of 12mm downgraded aggregates in the ratio 1:1 by weight. The jacketed members above the high tide level were coated with acrylic based curing compound immediately after the stripping of formwork. Figure-13 shows the completed view of the Fisheries jetty approach after jacketing with under water micro concrete.

Figure-13. A complete view after the jacketing with under water micro concrete.

8. POST REPAIR INVESTIGATION

After the Fisheries jetty approach was rehabilitated, half cell potential measurements were conducted on the piles after one year, as normally the experience of the maintenance engineers was such that within a year, the corrosion cracks reappear at the neighbouring places and to check the performance of the repair methodology adopted, especially the provision of the self regulating galvanic anode Galvanic anode, Half cell potential survey was conducted. Figure-14 shows the view of the half cell potential test in progress after the rehabilitation. Care was taken to ensure that the same locations before repair were again subjected to half cell potential test to assess the efficiency of the self regulating galvanic anodes.

Figure-14. A view of the half cell potential test after the rehabilitation.

Discussion based on the half cell potential readings

The half cell readings taken before and after completion of the rehabilitation and at interval of one year from the date of completion of the rehabilitation are listed in Table-4. The half cell potential reading values show values more positive than -200 mV at the end of 1 year and as per the recommendations of ASTM C-876 the rehabilitated structural members have high probability of no corrosion. Hence, it is clearly evident that the self regulating galvanic anode galvanic anode system is performing well in terms of corrosion protection.

9. CONCLUSIONS

In order to rehabilitate and improve the corrosion resistance of Fisheries jetty approach, half cell potential, carbonation test and chloride test were conducted on the various structural elements. Based on the analysis of the half cell potential readings and chloride content a repair methodology was designed which included micro concrete jacketing and provision of Galvanic anodes. The following are the conclusions drawn based on the post repair investigations:

The half cell potential measurements reveal that the integrity of the concrete in the rehabilitated structural elements of the Fisheries jetty approach is good, indicating the efficiency of the corrosion prevention technique designed and executed. The Fisheries jetty approach has not shown any distress on account of corrosion even after a period of 1 year as evident from the half cell potential readings taken after one year. The provision of galvanic anodes i.e., the galvanic protection system is performing well in the Fisheries jetty approach and from the pattern of the half cell potential readings observed over a period of 1 year, it may be concluded that this may continue to perform well for a few more years without causing any problem. In addition to that, even if the corrosion reoccurs after probably 6 years, it is required only to cut open the particular place to install another piece of galvanic anode instead of resorting to an expensive large scale rehabilitation measure resulting in closing down of the operation of the Fisheries jetty approach during the period of rehabilitation.

It can be concluded that the galvanic protection using the galvanic anodes are techno commercially a viable system to be adopted for the rehabilitation of the corrosion damaged marine structures and they can be a useful tool to be installed even during the construction of the marine structures resulting in considerable savings to the government agencies.

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