



ReBuild

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REBAR CORROSION PROTECTION

Dr. Fixit Institute
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India having more than 3000 kms of coastline loses more than ₹ 2 lakh crore a year - about 4 percent of the size of the total economy - due to corrosion in infrastructure and industry segments. In case of buildings and civil structures, a large proportion of such damage is caused due to insufficient planning and incorrect assessment of environmental attack such as carbonation and chloride exposure. The RCC structures are very much susceptible to environmental attack and can severely reduce the strength and life of these structures due to corrosion of reinforcement.

The factors that influence the corrosion of steel reinforcing bars embedded in concrete need to be controlled to an acceptable level, by which the resulting concrete deterioration can be minimized. This is the first step in most corrosion-control strategies in addition to other suitable corrosion-protection systems. Corrosion-control methods or systems are classified as mechanical or electrochemical. Mechanical methods are physical barriers that prevent or delay the ingress of chlorides, oxygen and moisture through the concrete cover to the reinforcing steel. They include admixtures, sealers and membranes, overlays, and coatings on steel reinforcing bars. Sealers and membranes made with materials such as resins, epoxies, emulsions, etc. are used to reduce the ingress of deleterious species. There are concerns about their effectiveness and durability on the traffic-bearing surfaces (bridge decks) due to the abrasion of applied sealers or the cracking of installed membranes. Coatings used on steel reinforcing bars are either organic or metallic. Organic coatings include the non-metallic fusion-bonded epoxy coatings. Metallic coatings include materials such as nickel, stainless steel and zinc. The nickel and stainless steel coatings protect steel by being a barrier system and more noble, i.e. have a lower potential than iron to corrode. The zinc coatings protect steel by being sacrificial or more active (i.e. it has a greater potential than iron to corrode). Corrosion-resistant material includes austenitic stainless steels and fiber-reinforced polymer (FRP) rebars.

The corrosion protection method is also recognized as a means of prevention of corrosion damage in new structures, where for a small percentage of the capital cost the design life expectations can be met without repeated and expensive repairs. For prevention of corrosion of existing RCC structures migration of corrosion inhibitor of sodium monofluorophosphate is most suitable method. It creates high vapour pressure at the surface thus forcing these inhibitor molecules to traverse inside through the pores of the concrete for forming a protective layer around the rebar. Where ever carbonation is the major cause of corrosion, in such structures anti-carbonation coating of acrylic based is most suitable. It can also be used in marine and industrial environments.

Electrochemical methods force the steel reinforcing bars to be cathodic. They include chloride extraction and cathodic protection. Chloride ion extraction and cathodic protection

are typically used to the rehabilitation of reinforced concrete structures and not as a corrosion-control measure for new construction.

Cathodic protection is designed to halt all the active corrosion and prevent new sites from developing corrosion. Although it has been used for immersed and buried structures for over 100 years, cathodic protection of reinforced concrete by means of an impressed current has been widely used only since the early 1980s. Cathodic protection is an economical alternative to patch repairs in chloride-damaged structures, not only because it provides a long-term solution but also because it obviates the need for massive removal and replacement of contaminated concrete. It is also cost-effective in severely carbonated structures. It is now used extensively as a means of corrosion control in concrete and has been applied to a wide variety of structures in coastal regions in Australia and America. The most recent development in cathodic protection of concrete structures is the internal anode system, where probe anodes, usually made from titanium mesh ribbon, are placed in drilled holes in the concrete surface and embedded in grout.

Electrochemical chloride extraction methods helps to reduce the chloride ions from the surroundings of reinforcing steel in contaminated concrete down to a level below the threshold limit for corrosion. On the contrary, electrochemical realkalization is the method where the carbonated concrete is again realkalised which helps in preventing the corrosion of rebar.

However, there are three categories of variables that influence the corrosion process and the extent of the corrosion-induced deterioration of reinforced and prestressed concrete members - material, design and environmental variables. Material variables for making durable concrete include cement type, admixtures, aggregate type and gradation and the water cement ratio. Design variables include the depth of concrete cover, physical properties of the hardened concrete, the size and spacing of the steel reinforcing bars, and the efficiency of drainage from the structure. Environmental variables include the source of chloride ions, temperature extremes, wet-dry cycles, relative humidity, and, to a certain extent, applied live loading.

Although little can be done to control environmental variables, material and design variables can be adjusted to build durable concrete structure that can resist corrosion-induced deterioration in environments conducive to the initiation and sustenance of the corrosion process. Since rebar corrosion is the most widely pervading ailment of concrete construction, we decided to present this issue of ReBuild to our readers with all interesting and advanced methods for corrosion protection including some case studies.

Corrosion Prevention Strategies

[Excerpts from [http://concreteconstruction.net/Images/Corrosion % 20 Protection % 20 for % 20 Reinforced% 20 Concrete_tcm45-356632.pdf](http://concreteconstruction.net/Images/Corrosion%20Protection%20for%20Reinforced%20Concrete_tcm45-356632.pdf)]

1.0 Introduction

There are mainly two major causes of steel corrosion in concrete - chloride attack and carbonation. The reinforcing steel is well protected in Portland cement concrete by a passive oxide layer film because of high pH of concrete. Once this layer is broken, either due to carbonation or ingress of chloride ions, the steel reinforcing bars are depassivated and corrosion occurs. Corrosion accelerates due to presence of oxygen and moisture, along with low resistivity of concrete and lower concrete cover. However, the intrusion of chloride ions is the most important factor in the corrosion of steel reinforcing bars embedded in concrete. Possible sources of chlorides include: aggregates, mix water, admixtures (accelerators) and seawater. The resulting corrosion products occupy volumes several times that of the volume of steel. The increased volume induces tensile stress in the concrete that results in cracking, delamination and spalling (Fig. 1). As a result, the reinforcements are exposed to direct environmental attack and the corrosion is accelerated.

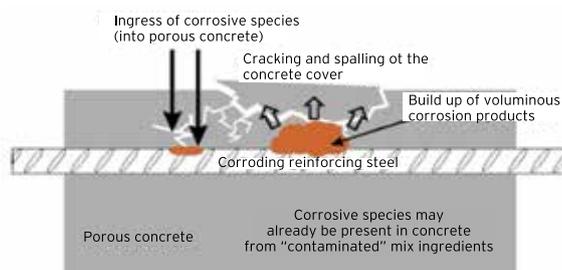


Fig. 1: Reinforcement corrosion process

There is a need to find ways and means to save maintenance costs due to corrosion and offer right solutions to enhance the life of buildings, plants, machinery and civil structures.

2.0 Corrosion Prevention Methods

Concrete can be protected from corrosion in three ways:

- Seal the surface of the concrete to prevent ingress of chlorides, carbon dioxide, moisture etc.
- Modify the concrete to reduce its permeability, thus increasing the time it takes for the chlorides to reach the reinforcing steel.
- Protect the reinforcing bars to reduce the effects of chlorides when they do reach the steel.

More and more designers are specifying multiple level of protection for structures that are at risk of chloride-induced corrosion. For example, it's now common to specify post-tensioned parking structures containing epoxy-coated reinforcing steel and silica-fume concrete.

The corrosion control strategies presented herewith discuss briefly on basic mechanisms of the control methods, expected performance, possible problems and relative costs.

3.0 Good Concrete Practice

Good concrete practices should be followed for all concrete but are sometimes not specified or the specifications aren't enforced on the jobsite. The following good construction practice tips are taken from the ACI Building Code (ACI 318):

- Maintain a low water-cement ratio. At a constant cement content, concrete permeability decreases as the amount of water per cubic meter is reduced.
- Provide adequate cover over the reinforcing steel. This helps increase the time it takes for the chlorides to reach the steel.
- Consolidate the concrete thoroughly. The advantage gained from using a low water-cement ratio will be lost if the concrete is not adequately consolidated. Using an HRWRA (High Range Water Reducing Admixture) can help here too.
- Provide adequate curing. Allowing fresh concrete to dry without curing the equivalent of at least seven days of wet curing reduces hydration and increases permeability.

In addition to these principles from the code, include the following practices.

- Use a high-range water-reducing admixture (HRWRA) to give the concrete enough workability so workers aren't tempted to add water in the field.
- Use of mineral additives cements such as flyash, silica fume or GGBS based blended helps to achieve a concrete having denser microstructures.
- Use post-tensioning to minimize cracking, where appropriate.
- Include provisions for repairing cracks in the original specifications.

Performance: The level of performance reached by following good concrete practices may not be all that's needed to protect reinforcing steel under severe conditions. But good concrete practices are the critical first steps in controlling corrosion.

Possible problems: Specifications aren't always enforced at the jobsite.

Relative cost: Low.

4.0 Latex-modified Concrete

Latex-modified concrete is prepared by adding liquid styrene-butadiene latex to conventional concrete. A typical latex-modified concrete mixture contains 300 kg of cement per cubic meter. 15% latex solids by weight

of cement have a water-cement ratio of 0.35. The latex modifies the pore structure of the concrete and reduces its permeability. Rapid chloride permeability testing on latex-modified concrete shows it to fall consistently into the very low range.

Performance: Good to excellent.

Possible problems: Cracking problems have been associated with some latex-modified concrete installations. Some state agencies specify that it be placed in the evening or at night to reduce cracking.

Relative cost: High.

5.0 Silica-fume Concrete

Silica fume is an extremely effective pozzolanic material that reacts with calcium hydroxide in hydrated Portland cement paste to form additional cementitious material. As a result, the permeability of the concrete is significantly reduced. Typical silica-fume concrete mixtures contain 300 kg of cement per cubic meter, 8% to 10% silica fume by weight of cement, a water-cement-plus-silica-fume ratio less than 0.40, and enough HRWRA to provide a 150 to 200 mm slump.

Performance: Good to excellent when tested using the rapid chloride permeability test (AASHTO T 277), silica-fume concrete is in the very low range, equivalent to latex-modified concrete.

Possible problems: Plastic shrinkage cracking has been a recurrent problem because of the low water content of silica-fume concrete and the lack of bleeding.

6.0 Membranes and Sealers

Applied to the concrete surface, membranes and sealers help prevent chloride entry. Membranes, which may be urethanes, neoprenes, or epoxies, are usually built up in multiple layers and frequently have the ability to bridge cracks in the concrete. Sealers range from linseed oil to sophisticated Silanes and Siloxanes.

Performance: Poor to excellent. Much research and testing have been done on the effectiveness of various sealers.

Possible problems: Products vary significantly in how they perform. Some are solvent based, which may be prohibited in some areas. Most abrasion occurs. The effectiveness of all these materials decreases over time and they must be reapplied.

Relative cost: Low to high. There is a continuing maintenance cost that should be included when comparing costs.

7.0 Anti-carbonation Coating

The anti-carbonation coating is formulated to protect reinforced concrete and other masonry cementitious substrate that is directly exposed to atmospheric conditions like UV radiation, high humidity, heavy rain, industrial

pollution, and carbonation. It penetrates into the porous concrete substrate, producing an exterior masonry impermeable coating. Most of the anti-carbonation coatings are solvent-based composition of acrylic solution polymer, properly selected and graded inert fillers, light fast pigments and additives. Various types of Silicone enhanced, vinyl and polyurethane coatings are also suitable for anti-carbonation properties. The detail application methods are given as follows:

7.1 Surface Preparation for New Concrete Surfaces

New concrete / plastered surfaces must be allowed to cure for at least 6 - 8 weeks before coating. Unless sufficient curing is done, entrapped moisture will exert pressure on the coating membrane. All surfaces must be clean, dry and free of loose material, oil grease, etc. Light grit blasting should be done in case of concrete surface to ensure better cleaning and bonding. The concrete surface should be washed thoroughly with water to clean dirt and dust which may hamper decorative effect and bonding of the coating. Any previous growth of fungus and algae should be removed completely by vigorous wire brushing and cleaning with water. Treatment with proper biocide solution should also be done prior to the application to ensure complete removal of algae / fungal growth.

7.2 Surface Preparation for Previously Painted Surfaces

Alkyd paint if any should be sanded thoroughly to completely remove all loose particles. Mechanical methods are most suitable. Exterior surface previously coated with cement paint should be wire brushed and washed with water thoroughly and allowed to dry. Treatment for algae / fungal growth remains same as new concrete surface. All cracks should be treated appropriately using elastomeric sealant or crack repair materials.

7.3 Priming

To produce better bonding and surface finish, primer should be applied by brush or spray, diluting in 2:1 proportion with mineral turpentine. It should be allowed to dry for 2-3 hrs before application of finishing coat.

7.4 Finishing Coat

Two neat coats of anti-carbonation coating should be applied without any dilution. It should be ensured that over coating is done when the first coat is dry for 5-6 hrs.

7.5 Precautions and Limitations

Although a gap of 5 - 6 hours may be given between the two coats, in cold / humid climates, dry up time may be extended. The coating products should be stirred well before the use. Application should not be done when ambient temperature is below 10°C.

7.6 Areas of Application

As anti-carbonation, protective and decorative coating for bridges, flyovers, subways, underpass, parking garages, tunnels, chimneys, industrial structures, stadiums, and RCC water tanks. Also all concrete structures and cementitious exterior masonry plastered surfaces that are exposed to the extreme atmospheric conditions. Also all thin RCC structures having less cover such as facades, fins are other areas of application of anti-carbonation coating.

Performance: Very good. Anti-carbonation property mainly depends on barrier property of a coating and also coatings' permeability or resistance to diffusion to atmospheric CO₂.

Possible problems: The coatings of generic base of polyethylene, epoxy, tar epoxy, chlorinated rubber, bituminous, cementitious, silicone and silicate are not suitable for anti carbonation coatings.

Relative cost: Medium.

8.0 Epoxy-coated Reinforcing Bars

Precleaned reinforcing bars are protected with a coating of powdered epoxy that's fusion-bonded to the steel in an assembly line process. Typically, manufacturers have the capability to coat straight bars, but only a few can coat bent bars. The coating physically blocks chloride ions.

Performance: Poor to excellent

Possible Problems: Unless the bars are coated after bending, there's a potential for cracking and chipping of the epoxy coating during bending. Damage to the epoxy coating also may occur during field-handling of the bars.

Relative cost: Medium.



Fig. 2: Epoxy coated rebar for corrosion protection

9.0 Cathodic Protection

Cathodic protection controls corrosion of steel in concrete by applying an external source of direct current to the embedded steel. A metallic anode is embedded in the concrete and an electric current is applied to this anode and the embedded steel. This action forces the steel in the concrete to become cathodic, which provides the protection. Cathodic protection is the only way to stop ongoing corrosion in a concrete structure. Zinc casing is also being provided by attaching to the reinforcement

during the construction to act as a sacrificial anode (Fig.3) to prevent the corrosion of reinforcement.

Performance: Poor to excellent

Possible problem: Cathodic protection is viewed by some engineers as a complicated process that requires extensive pre-installation engineering and extensive post-installation monitoring.

Relative cost: High initial costs. Low to medium operating costs.



Fig. 3: Zinc casing in reinforcement as a sacrificial anode for corrosion protection

10.0 Inorganic Corrosion Inhibitors

Only one product is available in this category. Its active material is calcium nitrate. The admixture is added during batching.

Calcium nitrate disrupts the corrosion process by enhancing the formation of the passivating layer on the surface of the reinforcing steel. The nitrate ions compete with any chloride ions present to react with the free iron ions. If the ratio of nitrate to chloride ions at the level of the steel is greater than about one, the reaction will be between nitrate and iron to bind the iron into an oxide, which reinforces the passive layer on the steel (Fig.4). If the ratio is less than one, that is, there's more chloride ions will react with the iron to begin the corrosion process. During the chemical reaction between the nitrate and iron, the supply of nitrate ions is developed.

The dosage of the calcium nitrate product must be determined based on the anticipated chloride loading of the structure over its expected design life. Actual dosages range from 7.5 to 30 litres per cubic meter.

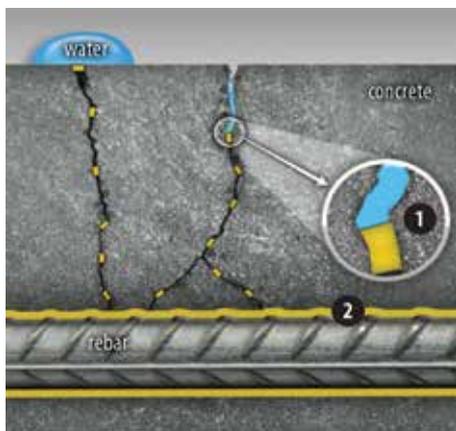
Performance: Good to excellent.

Possible problems: Nitrate is a component of some accelerating admixtures and accelerates set even when used in the corrosion protection role. Retarders are frequently used with the calcium nitrate to balance the set of the concrete. When higher dosages of calcium nitrate are used, the retarder may be added at the jobsite to reduce the problem associated with rapid loss of slump and rapid settings.

Dosage also can be a problem. To select the appropriate amount of calcium nitrate, a specifier needs a good idea of the amount of chlorides a structure will be exposed to.

When product is composited with other admixture, concrete trial is necessary to ensure its adaptability and air-entraining super plasticizer is not allowed.

Relative cost: Medium.



1. Hydrophobic pore blocking 2. Corrosion-inhibiting surface coating

Fig. 4: Corrosion inhibiting admixture acts as a hydrophobic pore blocking and creating a passive layer as corrosion prevention around the reinforcement

11.0 Organic Corrosion Inhibitors

Only one product is available in this category, and it is new to the concrete industry. It combines organic chemicals proven successful in inhibiting corrosion in applications other than concrete.

The admixture is added during batching. The organic corrosion inhibitor forms a protective barrier on the reinforcing steel. This barrier prevents reactions between the iron and chloride ions. The material also reduces the permeability of the concrete to slow the rate of chloride diffusion. This secondary effect plays a smaller role.

Because there are no competing reactions between the organic corrosion inhibitor and the chlorides, there's no need to estimate the chloride loading for the structure the chloride loading. The dosage is 3.75 litres per cubic meter.

Laboratory tests show the organic corrosion inhibitor functions well in cracked concrete. The barrier that is formed continues to function even when the chlorides have a straight path to the reinforcing steel in a crack.

Performance: Excellent based on laboratory testing. Some specifiers however are reluctant to try a product without an extensive record of in-place performance history.

Possible problems: Concrete containing the organic corrosion inhibitor requires a higher dose of air-entrainer.

Relative cost: Medium.

12.0 Migrating Corrosion Inhibitors (MCI)

It is based on amino carboxylate chemistry and usually the inhibitor is sodium monofluorophosphate which is mixed inhibitor of both cathodic and anodic. It increases the vapour pressure under normal conditions for migrating inhibitor molecules through the pores and after reaching metal surface form a mono molecular film. Fig.5 shows the corrosion inhibiting molecules migrate into the concrete and form a film around the reinforcement which act as a passivating layer to reinforcement and helps to prevent the corrosion of rebar. It can be surface applied by overlay or spray as shown in Fig.6.

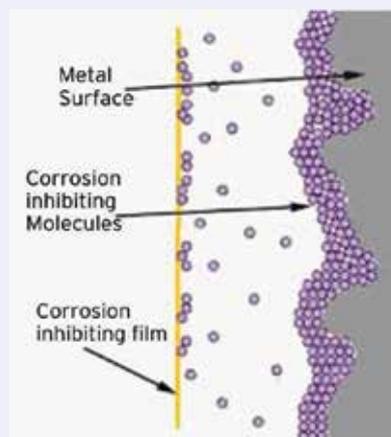


Fig. 5: Migration of corrosion inhibiting molecules



Fig. 6: Spray application for migration of corrosion inhibitors

13.0 Selection of Protection Systems

The proper corrosion-protection strategy will vary from structure to structure. Some factors to be considered during design of a structure include:

- Intended design life of the structure
- Effects of corrosion and corrosion-induced deterioration - This includes the costs due to closure (either permanent or temporary) for repair. Bridges on major roads are

more critical than bridges on local roads.

- Quality of workmanship in construction - The quality of construction entails good consolidation, proper rebar placement, sufficient concrete cover over the steel reinforcing bars, and other measures.
- Possible rehabilitation methods - The design of structures should include provisions for the possible future rehabilitation of corrosion-induced deterioration.
- Initial costs - May need to consider more than just initial costs (i.e. Life-cycle costs). As the rehabilitation and replacement costs increase, corrosion-control measures become more cost-effective.

14.0 Case Studies

14.1 Protection to Concrete Jetty-Panvel, Maharashtra

The jetty of a bulk cement terminal at Panvel, Maharashtra was damaged due to corrosion arising from the saline environment. The damaged RCC members of the jetty structure were restored to their original state using modern repair methods, and retrofitting and further corrosion was restricted by providing suitable acrylic based anti-carbonation protective coating as shown in Fig. 7.



Fig. 7: Protective coating to jetty at Panvel

14.2 Protection to Concrete Bridge - Mandovi Bridge in Goa

Mandovi Bridge, the bridge across river Mandovi which connects South Goa to North Goa was constructed during the early 1990s and has no protection against the attack of the coastal environment. The concern authorities after studying the properties of various types of polymer based coatings, selected combination system as the best protection proposed. This combination system consists of a silane/siloxane acrylic blend primer with a pigmented acrylic top coat. The job included sand blasting of the super structure (girders) and providing it with a coat of silane/siloxane acrylic blend primer.

Two layers of top coat using acrylic pigmented coating with silver grey colour was applied at a total wet film thickness

of 175 microns at a coverage of 0.35 ltrs per m² using airless spray equipment. The total surface area of the protection provided to Mandovi Bridge is about 16,000 m² which is at present considered to be one of the major jobs in the field of bridge protection in India. This job was executed during October 1998 to March 1999 as per the guidelines and specifications of the manufacture.

(Ref: <http://seminarprojects.com/Thread-protective-coatings-for-concrete-bridges#ixzz3o3Qn0l65>)

14.3 Surface Protection of Bankim Setu, Howrah

In the year 2002, in recognition of the importance and essentiality of surface protection systems on concrete bridges, the Public Works (Roads) Directorate of the Government of West Bengal published, as a part of its Schedule of Rates, a comprehensive set of specifications for such surface protection with the provision of waterproofing systems. In 2005, Eastern Railway included, as a part of its Schedule of Rates, a specification for the surface protection of concrete bridges. The emphasis, as in the case of PW (Roads) Directorate SOR's, was on coatings with phenolic resin based preparations.

Bankim Setu, an R.O.B. of Eastern Railway at Howrah Station, Howrah, West Bengal is very busy railway track at Howrah Station. The underside of the reinforced concrete deck, the prestressed concrete girders and piers were given surface protection with one coat of phenolic resin based coating compound, followed by a finish coat of phenolic resin based of dove grey colour matching the colour of concrete. The highly distressed bridge had to be repaired before the application of the surface protection system.

14.4 Surface Protection of Katakhalī Bridge on the Hasnabad- Hingalgañj Road, West Bengal

Surface protection was given to the central span of the multi-span Katakhalī Bridge on the Hasnabad- Hingalgañj Road, not too far away from the coasts of West Bengal. The bridge is over a wide river with fast flowing water. The newly constructed bridge had already shown early signs of minor distress. The surface protection treatments with phenolic resin-based coating were provided after local spots of the bridge were repaired. Though the superstructures of Katakhalī Bridge and Bankim Setu had similar surface protection treatments, the piers of the Katakhalī Bridge, in the river bed were provided with cement-based waterproofing treatment. This treatment is ideal in the environment of fast flowing water.

14.5 Surface Protection of Charki Bridge over the Ajoy river in West Bengal

Surface protection was given to the spans of Charki Bridge over the Ajoy river in West Bengal. The bridge

was provided with two coats of phenolic resin-based coating. Though phenolic resin-based coating has excellent resistance against water and many chemicals, the polymer is susceptible to decay when exposed to ultra-violet ray. As a solution, dry coarse sand was sprayed on the second coat of same phenolic resin based coating on the exterior faces of girders. All the types of treatment, when tested under a water head of 20 m, were found to have zero permeability. Many concrete bridges of East Coast Railways and other organizations were provided with acrylic coatings.

15.0 Conclusion

Concrete bridges, roadways and other structures of recent times, compared to such structures of earlier periods, have suffered early damages due to the use of inappropriate materials (both cement and reinforcing bars) and due to a lack of adequate curing.

Many of the problems, associated with the use of high strength rebars with surface deformations, OPC with high specific surface, high C_3S/C_2S ratios, blended cement, cement with excessive contents of water soluble alkalis and inadequate curing, can be alleviated if all exposed surfaces of concrete will be protected with waterproofing treatments.

The Indian code for concrete structures has mandated the provision of surface protection systems for the prevention of the ingress of water as one of the ways to make concrete structures durable. Several bridge authorities have adopted specifications for the surface protection of concrete bridges as a part of their schedules of rates. Many concrete bridges all over the country have been protected with the provision of surface coatings and other treatments in recognition of the fact that if left unprotected, as in the past, today's concrete structures, unlike concrete structures of earlier decades, will fail to be durable.

Multiple protection strategies may be cost effective for long-term corrosion protection. One such strategy is the use of epoxy-coated rebar in combination with a durable concrete containing corrosion inhibitors, having a low permeability, and adequate concrete cover. Silica fume and fly ash can be added to the concrete to reduce permeability and provide additional corrosion control. However, there is a need to balance the costs of the additional control measures against how much additional service life can be expected as a result of the added control measures. The additional costs can usually be justified based on a life-cycle costs analysis. Some factors to be considered when choosing a corrosion-control measure include:

- Reliability and effectiveness of the measure.
- Risk of unintended side effects.
- Possibility of future installation of other control measures.

Cathodic Protection of Reinforced Concrete Structures

[Extracted from "Understanding Corrosion and Cathodic Protection of Reinforced Concrete Structures", by Steven F. Daily, Corpro Companies, Inc. USA]

1.0 Fundamentals

There are many ways to slow down the corrosion process, however cathodic protection (CP) is the only technology that has proven to stop corrosion in existing reinforced concrete structures, regardless of the chloride content in the concrete. What is CP? Quite simply CP is a widely used and effective method of corrosion control. In theory it is defined as the reduction or elimination of corrosion by making the metal a cathode via an impressed direct current (DC), or by connecting it to a sacrificial or galvanic anode. Cathodic areas in an electrochemical cell do not corrode. By definition, if all the anode sites were forced to function as current-receiving cathodes, then the entire metallic structure would be a cathode and corrosion would be eliminated.

For decades, CP has been successfully used to protect underground pipelines, ship hulls, offshore oil platforms, underground storage tanks, and many other structures exposed to corrosive environments. The first application of CP to a concrete structure was a bridge deck in 1973. This system continues to function with no physical delamination of the concrete. CP of steel in concrete is quite simply a means of fighting fire with fire, or in this case, electricity with electricity. The corrosion process generates electric currents. CP supplies a source of external current to counteract the corrosion current. Hence, corrosion can be eliminated.

As indicated above, there are two types of CP systems - impressed current and galvanic. An impressed current CP system for concrete structures may require the following basic components:

- DC power supply (rectifier).
- Inert anode material, such as catalyzed titanium anode mesh.
- Wiring and conduit.
- Instrumentation, such as embedded silver/silver-chloride reference electrodes.

A schematic of an impressed current CP system using catalyzed titanium anode mesh is shown in Fig. 1.

A rectifier is used to convert alternating current (AC) to direct current. A rectifier works on the same principle as an AC adapter for a computer or a battery charger. In an impressed current CP system, the rectifier provides the power (i.e. low voltage direct current) and controls the amount of power to each zone. Rectifiers are available

in many types and operating outputs. Mainly, they are designed to provide either constant current or constant voltage to the anode system.

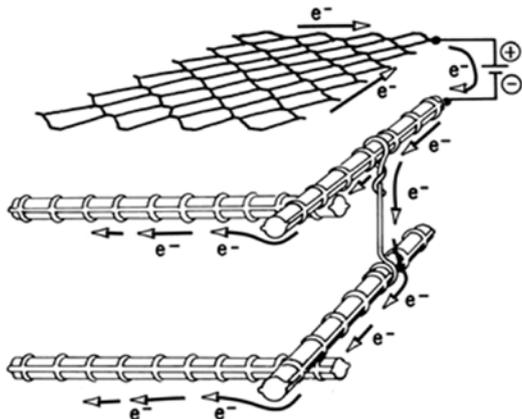


Fig.1: Schematic diagram of impressed current CP system

The anode is one of the most critical components for a cathodic protection system. It is used to distribute protective current to the reinforcing steel and provides locations for anodic reactions to take place in lieu of the reinforcing steel. By using relatively inert materials, such as catalyzed titanium, anode consumption is minimized. One of the main benefits of catalyzed titanium is that its life expectancy can be determined through accelerated life testing. N.A.C.E. Standard TMO294-94, "Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel-Reinforced Concrete" gives procedures for accelerated life testing of these anodes. Based on test results using this method, it has been found that the life of catalyzed titanium anodes can readily exceed 40 years for existing structures, and over 100 years for new reinforced concrete structures (i.e. cathodic prevention). Fig. 2 shows the application of titanium anode mesh to a bridge deck. The mesh is subsequently covered with a concrete overlay.



Fig. 2: Anode Mesh installation on a bridge deck

A sacrificial or galvanic anode system for reinforced concrete uses a more reactive metal (anode) such as zinc or aluminum-zinc-indium (Al-Zn-In), to create a current flow (Fig.3). Sacrificial anode systems are based on the principle

of dissimilar metal corrosion and the relative position of different metals in the galvanic series.



Fig. 3: Arc-spray application of sacrificial Aluminum-Zinc-Indium

The direct current is generated by the potential difference between the anode and reinforcing steel when connected. The sacrificial anode will corrode during the process and is consumed. Current will flow from the anode, through the concrete, to the corroding reinforcing steel. Galvanic anodes may be installed as cast anodes (Fig. 4) or thermally sprayed onto atmospherically exposed concrete to form a sacrificial coating. Fig. 4 shows the arc-spray application of an Al-Zn-In coating to a reinforced concrete bridge pier.

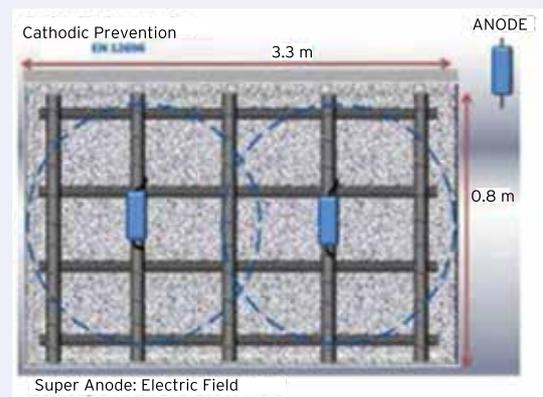


Fig. 4: Schematic diagram showing installation of Sacrificial Galvanic anode

Galvanic CP systems have the benefit of no auxiliary power supply and the advantage of being used for pre-stressed or post tensioned concrete without the risk of elevated potential levels, which can lead to hydrogen embrittlement of the steel. The anode life, however, may be relatively short as compared to the inert anodes, which are used with impressed current systems. Also, the current that is produced by a galvanic anode is a function of its environment, i.e. moisture and temperature conditions, and the output cannot be easily adjusted or controlled as with the impressed current method.

Reference electrodes are used to evaluate cathodic protection levels. They may be portable devices or permanently embedded probes in the concrete structure. The most commonly used embedded reference electrodes are silver/silver chloride (Ag/AgCl). Reference electrodes should have a separate ground connection to the reinforcing steel. CP systems also require a negative connection to the reinforcing steel (return path for electric current).

With CP, chloride ions will slowly migrate away from the reinforcing steel and toward the anode. Furthermore, the production of hydroxide ions at the steel surface will cause the concrete to revert back to an alkaline state. These factors when taken together will quickly arrest the corrosion process when current is applied, and allow the passivating film to reform on the surface of the reinforcing steel. It is important to realize that with cathodic protection corroded reinforcing steel cannot be restored to its original native state, but corrosion of steel in concrete can be effectively stopped through the application of cathodic protection.

When evaluating a structure as a candidate for cathodic protection, several parameters should be considered. These may include:

- Remaining service life should be > 10 years.
- Delaminations and spalls should be < 50% of structure area.
- Chloride content should be > 0.026% by weight of concrete.
- Half-cell potentials should be > - 200 mV, indicating a breakdown of the passivating film.
- The candidate structure should be structurally sound.
- The majority of reinforcing steel bars should be electrically continuous.
- AC power should be available.

The process of cathodic protection for reinforced concrete structures surprisingly takes little power. Data has shown that typical CP operating current densities range between 0.2 and 2.0 mA/m² for cathodic prevention of new reinforced concrete structures, as compared with 2 to 20 mA/m² for CP of existing salt contaminated structures. This will result in power consumption ranging from 1-3 watts per 1,000 m² of concrete for new construction, and 3-15 watts per 1,000 m² for existing structures.

Once the CP system has been installed it is necessary to provide routine monitoring and maintenance. For impressed current systems, this involves visual inspection of the system and periodic checks at the power supply to ensure proper operation. As a minimum, the periodic checks should entail measurement of the voltage and current for each anode zone. Ensuring the supply of direct current from the rectifier to the structure in accordance with the operation and maintenance manual is the most important operating parameter. Remote monitoring systems may also be incorporated to help facilitate monitoring of the

rectifier. As indicated above, galvanic anode systems have no power supply and therefore they require minimal monitoring and maintenance.

2.0 Development of Anode Systems

The high resistivity of concrete as an electrolyte has been an obstacle to the use of cathodic protection of reinforcement until recent years. Developments in anode technology since the 1980's have seen the emergence of a wide variety of anode systems for various applications:

2.1 High Silicon Cast Iron Anodes within a Conductive Asphalt Layer

These were one of the first developments for flat slabs, particularly bridge decks. The additional weight of the asphalt and its short lifespan were disadvantages which led to the development of alternative systems such as slotted anodes, where the conductive string anode was placed in a sawcut in the surface of the concrete. Various anode types were tried, platinum-clad niobium wire proving quite successful, but the high current density required gave rise to excessive generation of acidity at the anode. Conductive coatings, using carbon-laden acrylic paint as the conductive anode, have also proved popular in situations where additional weight must be minimized, but their lifespan is limited. Flame sprayed zinc is a new development of this approach.

2.2 Conductive Polymer Wire

This wire was popular in the early 80s but was superseded by the introduction of expanded titanium mesh anodes. These systems comprise an activated titanium mesh coated with mixed metal oxides, encased in a conductive cementitious overlay, often of gunite. The mesh configuration minimizes and spreads the current distribution over each protection zone of the concrete surface and thus reduces the risk of acid generation at the anode. This method remains widely used because of its effectiveness with very small current densities and the longevity of titanium. It is particularly suited to large concrete surfaces such as slabs and beams.

2.3 Installation of Titanium mesh

A more recent development in cathodic protection of concrete structures is the internal anode system, where probe anodes of activated titanium mesh are placed in drilled holes in the concrete surface and embedded in cementitious grout. This method has the advantages of negligible added weight, relative cheapness and the ability to protect distant rebars. It is particularly suited to massive elements such as beams and columns but not to thin slabs.

3.0 Case Studies of Cathodic Protection Systems

Both the titanium mesh and internal anode systems are becoming widely used on concrete structures around the

world. Some early examples of remedial projects are:

3.1 A floor slab in a Sydney apartment building

It was found to have suffered extensive corrosion of top mat reinforcement arising from the use of a chloride-rich magnesite topping. Conventional patch repairs would have required the removal of all the top 100 mm of concrete and would have promoted corrosion of the bottom mat steel; cathodic protection was therefore considered the only practical method of rehabilitation. A titanium mesh system was installed within a 25 mm concrete topping and the protection levels have been found to be satisfactory since it's energising in 1989.

3.2 An eight-storey apartment building in Auckland, New Zealand

It had been seriously damaged by wind-blown chloride contamination and carbonation in its structural concrete frame, since construction 56 years ago. Conventional patch repairs had been attempted during a major renovation in 1982 and had subsequently failed. A titanium mesh anode system in four zones was placed on all external beams and columns in 1990, and successful polarization of external face steel was achieved within three months. Over two years of operation, protection has developed gradually in the internal-face reinforcing steel as far as 800 mm from the anode mesh.

3.3 A bridge abutment at Frankston, Victoria

It was found to be severely contaminated by water-borne chlorides. Corrosion levels were highest in the tidal zone at the base of the abutment and lowest in the atmospheric zone. A titanium mesh anode divided into three horizontal zones was installed and encased in a layer of gunite in 1991. Protection levels were achieved in each zone with markedly different current densities.

3.4 A housing estate in Copenhagen, Denmark

It comprises 1943 apartments in 17 blocks and was found to have extensive corrosion of reinforcement in most of the beams and columns in the access balconies. Each beam/column set required 13 internal anodes and approximately 40,000 in total were installed between 1990 and 1992. All elements were connected to a central personal computer which monitors and controls the system and each anode.

3.5 A wharf at King Island, Tasmani

It was contaminated with chlorides to the extent that much of the cast in-situ beams and precast deck soffit was cracked or delaminated. A titanium mesh system encased in gunite was chosen for 1300 m² of concrete requiring treatment; the installation was completed and energised in mid 1992.

3.6 A road and rail bridge at Weipa, Queensland

It was found to have significant chloride contamination in its precast concrete piles and in-situ concrete headstocks

across 1.1 km of trial estuary. Trials of different Cathodic Protection systems were undertaken on four piers. On the tidal and splash zones of the piles, mesh anodes were installed in modular foam-lined FRP shells, cement-grouted FRP shells and fabric-formed concrete jackets. Underwater, titanium rod anodes were installed at each pier. In the atmospheric zone of the piles and headstocks, internal anodes were used. The final design chosen was for internal anodes on headstocks and upper piles, combined with immersed rod anodes for the underwater sections of pile. Installation was completed in 1995.

3.7 Draft CT of HPCL Mumbai Refinery

The mesh ribbon was used as anode in new force draft CT of HPCL Mumbai Refinery with cathodic protection system for corrosion protection in year 2013 (Fig. 5).

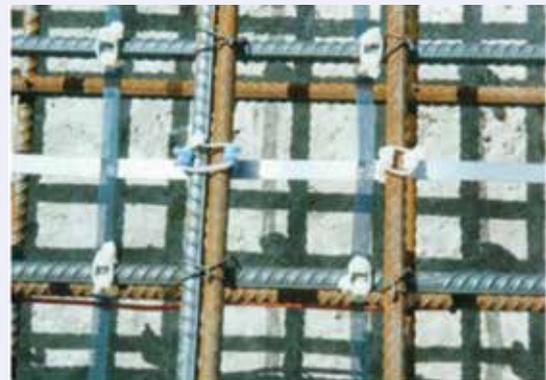


Fig. 5: Ribon anodes being used for Cathodic protection

4.0 Conclusion

It is normal for a Cathodic Protection system to be tuned over the first two years or so of operation as potentials stabilize and current demands reduce. Monitoring of protection levels and trends is therefore required at intervals of three or six months in the initial stages and annually thereafter, until the system has balanced and needs only regular checking of its operational status.

Cathodic Protection has become accepted and widely used as a means of halting corrosion of steel in deteriorating reinforced and prestressed concrete structures. The advantages of Cathodic Protection over other rehabilitation methods can be summarized as follows:

- Cathodic Protection has the ability to stop the corrosion process for the extended life of the structure.
- Cathodic Protection is a long-term solution (in excess of 25 years), with minimal maintenance requirements.
- Cathodic Protection exhibits long-term economical advantages when discounted over the design life of the system. In many cases, the first cost may be less than a conventional patch repair, with a life four to five times longer.

Pros & Cons of Chemical & Electrochemical Corrosion Protection Techniques for Reinforced Concrete Structures

[Extracted from Editorial, International Journal of 3R's, Vol. 2, No. 4, 2011, p.p 309 - 310]

1.0 Introduction

It is well known that one may make use of several electrochemical techniques in order to repair the concrete structures damaged due to reinforcement corrosion or to protect the new ones in highly aggressive environment. None of the techniques are universally applicable or completely foolproof or always economically viable. Hence a repair professional has to appreciate the merits and limitations of these techniques. The various pros and cons of the following methods that are quite prevalent in the construction industry are discussed herewith.

2.0 Corrosion inhibitors

Diffusing corrosion inhibitors into the concrete to protect the steel is a relatively new approach to concrete repair. The range of inhibitors is quite large, viz., several proprietary formulations of vapour phase inhibitors based on amino alcohols that create a molecular layer on the steel to block corrosion; monofluorophosphate that may create a highly alkaline environment as it hydrolyses in the concrete; calcium nitrite (an anodic inhibitor) in a mixture, to help penetration into concrete. The use of calcium nitrite as a corrosion inhibiting admixture in the concrete mix is well established. However, trials of inhibiting treatment in hardened concrete after corrosion damage are comparatively recent.

The main advantage of corrosion inhibitors is that the application is comparatively inexpensive and simple for any element with an accessible surface. However, the knowledge and understanding of the range of inhibitors is limited. The issues that need consideration in this context are their penetrability into concrete, uniform and effective spread along the rebar network, corrosion suppression capability, time-dependent effectiveness, the level of corrosion that can be countered, etc. Since answers to all these queries are not readily available, the use of corrosion inhibitors is restricted to concrete having carbonation or low-to-moderate chloride levels (less than one percent by weight of cement), low reinforcement cover (less than 20 mm), etc.

3.0 Cathodic Protection

Cathodic Protection has certain variants. The oldest and the most well established, is the "Impressed Current Cathodic Protection (ICCP)". The technique involves the application of a low voltage DC (typically 10V at 1A) from

a permanent anode usually positioned on the concrete surface to the reinforcing steel. There are a number of anode types which include conductive coatings, overlay system (coated titanium mesh in sprayed concrete), etc. New anodes are being continuously developed. It appears that if carefully designed, an ICCP system can provide a less invasive method of concrete repair than traditional methods. For long residual service life (say, 20 years or more) the life cycle cost analysis of ICCP often appears favourable. However, the ICCP system requires continuous monitoring for the life of the structure by suitably trained persons. Further, this method cannot be applied to elements containing prestressing steel or structures susceptible to ASR or with a lot of electrically discontinuous steel and so on.

Another variant of Cathodic Protection is the use of galvanic or sacrificial anode, often acronymed as GP. The sacrificial anodes, composed of a more reactive metal than steel (usually zinc), corrodes preferentially to the steel as a result of a difference in potential between the two metals, thus providing the necessary current required to maintain the reinforcing steel in a cathodic state. However, since concrete has a high resistance, galvanic systems are usually applied to structures in very wet conditions such as in tidal marine exposure. Recent developments are leading to trials of humectants, which humidify the concrete and lower the resistance, making galvanic cathodic protection more viable in a wider range of applications.

A third variant of Cathodic Protection, known as Discreet Galvanic Anode System (DGA), utilizes sacrificial anodes buried in a patch repair in order to provide localized protection to reinforcing steel. These galvanic anode units have been specifically developed to complement traditional patch repairs and consist of zinc anodes encased in a specially formulated mortar to maintain long-term galvanic activity of zinc. This is a simple and yet effective method of avoiding the transfer of corrosion to the previously protected region in which the incipient anode effect is observed.

4.0 Electrochemical Chloride Extraction

This method, often abbreviated as ECE, refers to a process of reducing chloride ions from the surroundings of reinforcing steel in contaminated concrete down to a level below the threshold limit for corrosion. In this process a temporary externally mounted metallic anode as shown in Fig. 1 is embedded into an alkaline electrolyte reservoir and a current (typically 1 A/m² of concrete) (Fig. 2) is applied to the reinforcing steel which becomes the cathode. The negatively charged chloride ions are repelled away from the negatively charged reinforcing steel and migrate towards the positively charged anodic mesh (Fig. 3). Simultaneously, the electrolytic production

of hydroxyl ions at the steel surface also results in the displacement of chloride ions and subsequent repassivation of the steel with an effective buffer zone.

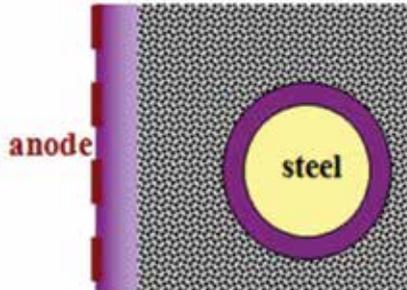


Fig. 1: Installation of metallic anode for electrochemical chloride extraction

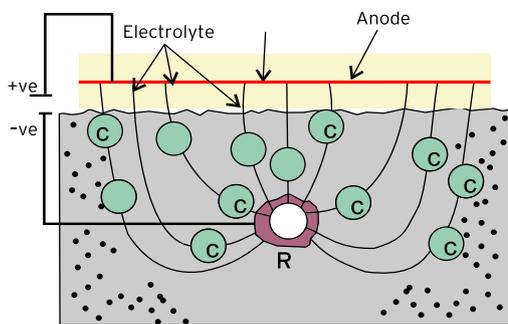


Fig. 2: Making rebar as cathode by installation of external current

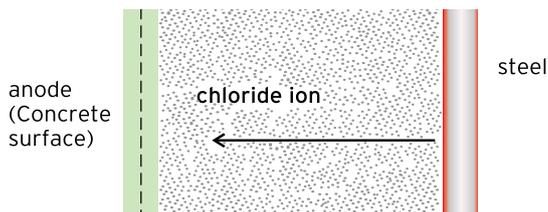


Fig. 3: Negatively charged chloride ions being migrated towards the positively charged anodic mesh

ECE is observed to be at its best where the steel is reasonably closely spaced, where the chlorides have not penetrated too far beyond the first layer of reinforcing and where future penetration of chlorides can be excluded. The treatment reportedly takes about 8 weeks. On completion the current is switched off, and the external anode with its electrolyte reservoir is removed and discarded, as there are no ongoing monitoring requirements. Thus, one may take it as a one-off treatment. But it might be worthwhile to consider that the problems with isolated steel, prestressing, ASR, etc., mentioned for ICCP, are exacerbated for ECE owing to the higher voltages and current densities.

5.0 Electrochemical Realkalization (ERA)

This is generally regarded as the equivalent of ECE for structures where the carbonation has progressed to unacceptable depths. ERA works on the basis of electro-

osmosis and is used to realkalise carbonated concrete by making the existing reinforcement as the negative electrode or cathode and by installing a temporary external metallic anode mesh embedded in a disposable electrolyte mass containing a molar potassium carbonate based solution. On applying a voltage between these electrodes, the electrolyte is drawn towards the reinforcement. The movement results in ionic migration under the influence of the applied current and electro-osmosis. This action pulls the ERA electrolyte into the concrete pores. In the course of 7 - 10 days the concrete gets saturated to beyond the cover zone with the alkaline solution reinstating the pH level to the desired extent. The schematic representation of electrochemical realkalization is shown in Fig. 4.

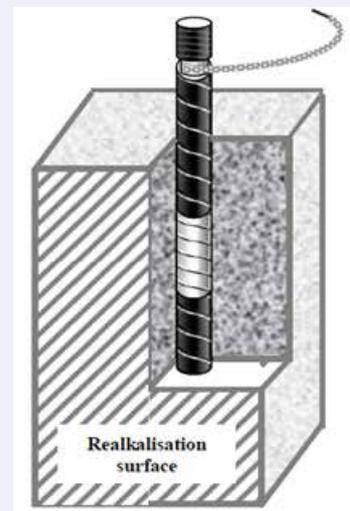


Fig. 4: Schematic representation of electrochemical realkalization process

6.0 Conclusion

From the above discourse, it is evident that adequate knowledge of the electrochemical process of reinforcement corrosion is necessary in order to understand, assess, and specify the most appropriate repair technique. It is well known that since 1980s the main focus of concrete repair research has been on the electro-chemical methods to protect the reinforcement against corrosion. These research efforts have yielded different options as narrated above with varying advantages, disadvantages and applicability. But the practices have shown that in the case of chloride induced corrosion that it is more prudent to undertake the prior diagnosis of the whole concrete surface than taking discreet samples from certain selected points. The potential mapping in close parallel lines over the entire surface gives the information of the probability of corrosion over the whole investigated surface. The potential maps are a basis to decide which repair methods should be used in which areas.

Corrosion Repair and Protection Measures - A Case Study

[Excerpts from International Journal of 3R's, Vol.2, No.4, pp-337-345]

1.0 Background

A corner located commercial building in South Mumbai got damaged due to corrosion of reinforcement for which repair and rehabilitation was needed. The present case study discusses the step by step approaches that were adopted for repair. The damage was to such extent that the RCC sunshade collapsed while removing the waterproofing layer on top of it. This building was very close to sea coast. The corrosion took place due to ingress of chloride ions. There was combined effect of carbonation and chloride ingress for accelerating the corrosion and damaging the structural members of columns, beams and slabs. The basic scope of the project assigned was for general repair, structural repair, and terrace waterproofing, part replacement of sanitary and plumbing, external waterproofing, re-plastering and then common area painting and external protective coating.

2.0 General Repair

2.1 Breaking of Plaster and RCC Sections

The vertical fins, which were just for elevation purpose, were suggested for their removal completely to reduce the dead load and future maintenance cost. This took considerable time to break the RCC along with its reinforcement and to level the broken area as per the elevation design.

2.2 Recasting of RCC Sunshade

It was suggested that a continuous sunshade Fig.1 be constructed for protection against rainwater, instead of the old sunshades just over the window openings. This helps prevent water running over empty spaces along the walls that results in the growing of moss and fungus, which causes the appearance of black spots and spoils the paint. All new re-bars were anchored to the beam with the help of FISCHER epoxy resin capsules and 100 mm thick reinforced concrete was cast uniformly with the help of waterproof ply shuttering.



Fig. 1: Continuous sunshade being provided after breaking damaged parties

2.3 Plastering

Old and new plaster was joined using a bonding adhesive for proper bonding. PP (Polypropylene) Fibres were used as transverse reinforcement to join the first and second coats of plaster consecutively, in 1 : 4 and 1 : 3 cement mortar ratio. Liquid waterproofing compound was added as an admixture in the mortar. The gaps between the RCC and masonry were filled by a polymer modified mortar, embedded with metal aggregates. Fresh pointing was done in loose brickwork wherever bedding and jointing mortar had disintegrated. Dash coat plaster was provided wherever loss of brick/block work required the application of a mortar thickness of more than 25 mm.

2.4 RCC Coping

To prevent leakage on top of the parapet, RCC coping was laid over at a height of a 1.04 m parapet wall with 25 mm projecting outside, 75 mm projecting inside and a top finish of a 25 mm inward slope. Making shuttering on three sides has no complication because of the scaffolding support. The fourth side was also cast with additional safety measures.

3.0 Structural Strengthening

The external columns, beams and slabs on the ground floor and the columns and beams on the top most floors deteriorated very badly and were repaired with a polymer modified mortar and micro concrete. Fibre wrapping on few columns was done to enhance the strength of these weak columns.

All the old bars were cleaned with rust remover. 24 hours after application, the surface was cleaned with water jets so that all rust and loose concrete was cleaned thoroughly. Wherever reinforcement bars lost more than 25% of their original diameter volume, additional rebars were provided as replacement/replenishment. Old and new bars were coated with a rust preventer, as a passivator coat. One or more coats were applied using a ready-to-use powder that was mixed with water and modified with powder polymers. The new reinforcement was connected to the original concrete by fixing Shear Connectors, using polyester resin anchor fix grouts. These connectors were fixed using a chemical based grout that has high pullout bond strength by drilling a hole into the concrete of a minimum of 100 - 150 mm in depth. It was ensured that the pullout strength of that anchor was more than the tensile strength of the bar. After 24 hours, the entire surface was coated with a long pot life epoxy bond followed by a watertight shuttering, prepared to pour micro concrete.

The beams and slabs in the basement were damaged as shown in Fig. 2 due to leakage from the common WC

block on the ground floor which were jacketed with micro concrete by drilling a hole from the top floor (Fig. 3).



Fig. 2: View of roof slab before micro concreting



Fig. 3: View of roof slab after micro concreting



Fig. 4: Column before micro concreting



Fig. 5: Column after micro concreting

A portion of the slab bottom sagged and de-bonded. By providing watertight shuttering, slab casting was done using micro concrete with 6 mm down pea gravels poured from the top floor by making a few core cuttings for maximum flow up to 2 metres (Fig. 3). Similarly the damaged columns were strengthened with micro concreting. Fig. 4 and Fig. 5 show the column before micro concreting and column after micro concreting respectively.

4.0 External Protective Coating

The external surface of the building was protected again with good quality coating that had elastomeric properties. A hand roller was used for application instead of a brush. Three coats were applied with the hand roller as per manufacturer recommendations. Acrylic coating was used having crack bridging properties. This is very important for old buildings. A five year warranty against leakage was received and given to the client stating that the manufacturer will give free material during the tenure of the contract and the contractor will apply the material at no extra cost to the Society during the defect liability period. Fig. 6 and Fig. 7 show the external treatment with primer and finished coat respectively.



Fig. 6: View after primer coat



Fig. 7: View after final coating

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Date : 15 - 19 June 2015

Venue : DFI-SPR, Mumbai

Participants : Engineers of Indian Oil from all over India

Topic : Waterproofing in New RCC Buildings- Specifications, Materials and Methodology

Date : 25 - 26 June 2015

Venue : DFI-SPR, Mumbai

Participants : HAL, Cipla Ltd, Rutu Group, Wacker Chemie India Pvt. Ltd., Container Corporation of India, Delhi, M/s. Stanford Engineering

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Sr. No.	Date	Venue	Topic	Fees	Details of the topic
1	30 Nov to 11 Dec 2015	DFI - SPR, Andheri (E), Mumbai	Entrepreneurship in Waterproofing, Structural Protection and Repair of Concrete Structures	₹ 10000	<ul style="list-style-type: none"> Waterproofing - practices, materials and application techniques Building maintenance and general repair Safety, health and environmental aspects Entrepreneurship development Practical sessions
2	21 & 22 Jan 2016	DFI - SPR, Andheri (E), Mumbai	Concrete Durability - Analysis of Codal Provisions and Right Methodologies	₹ 4600	<ul style="list-style-type: none"> Understanding durability of concrete and its codal provisions Effects of aggressive environments on concrete durability Making of durable concrete - precautions in successive steps Protective coatings for ensuring durability

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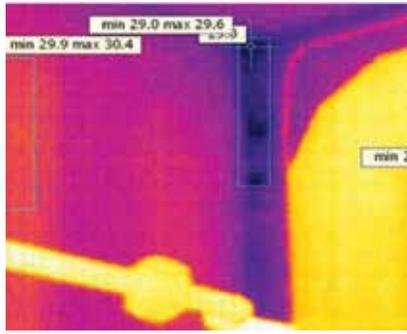
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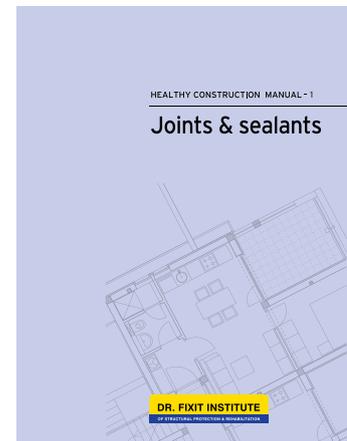
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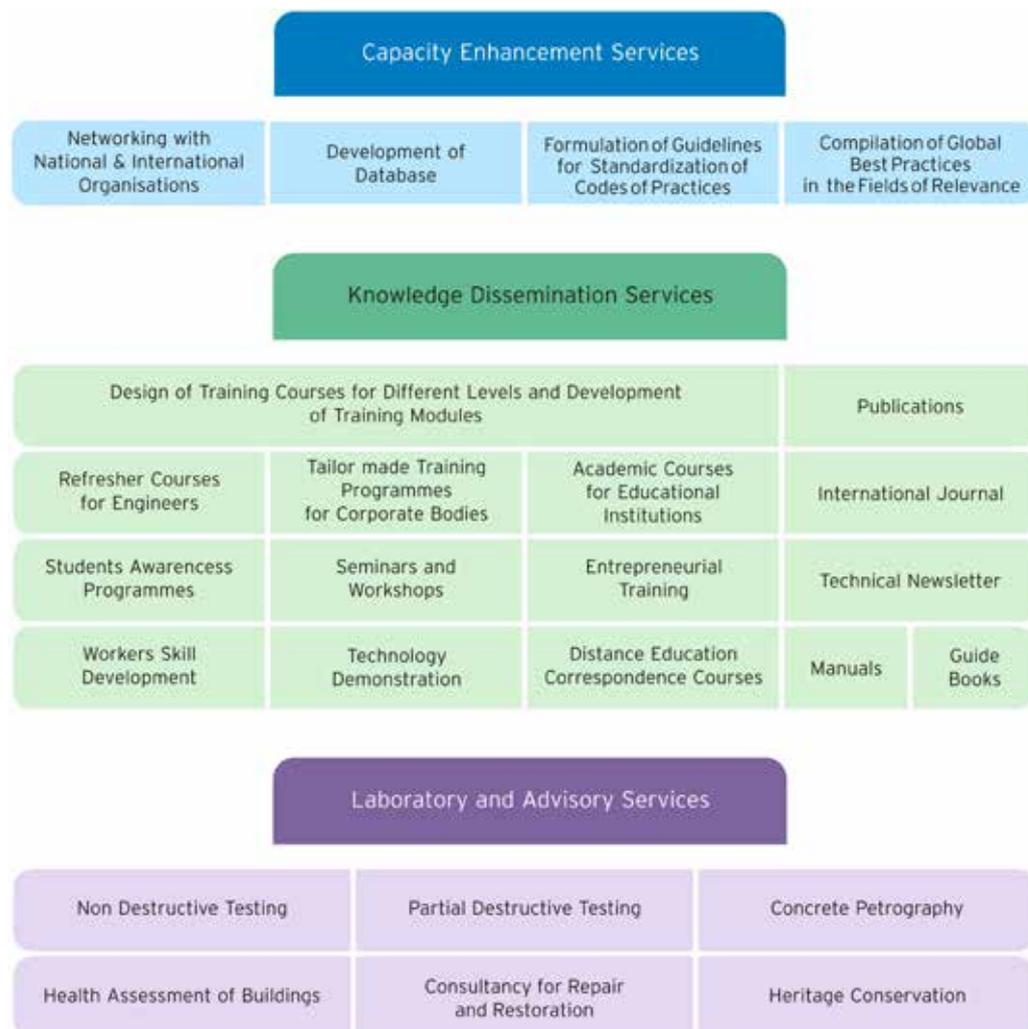
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