Corrosion Prevention Strategies

[Excerpts from http://concreteconstruction.net/Images/Corrosion % 20 Protection % 20 for % 20 Reinforced% 20 Concrete_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.

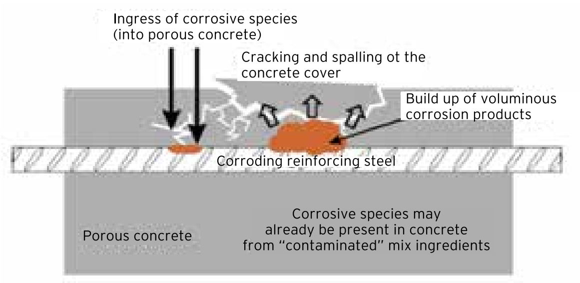


Fig. 1: Reinforcement corrosion process

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^{o}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 CO_2.

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.

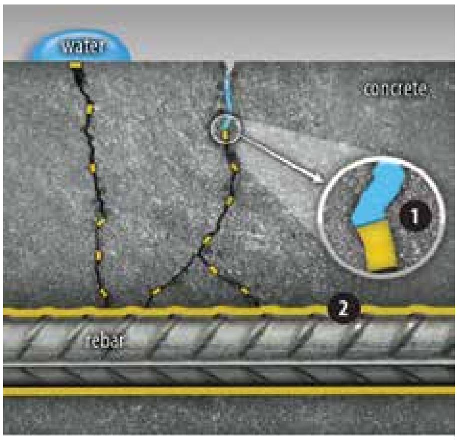
Performance: Good to excellent.

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 carbooxylate 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 migratae 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 applied as shown in Fig.6.

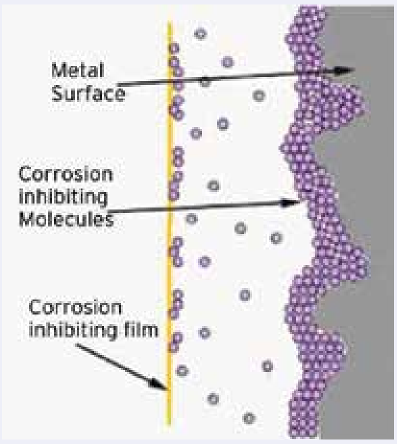


Fig. 5: Migration of corrosion inhibiting molecules

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 m^2 using airless spray equipment. There total surface area of the protection provided to Mandovi Bridge is about 16,000 m^2 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#ixzz3o3QnOl65)

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 Katakhali Bridge on the Hasnabad- Hingalganj Road, West Bengal

Surface protection was given to the central span of the multi-span Katakhali Bridge on the Hasnabad- Hingalganj 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 Katakhali Bridge and Bankim Setu had similar surface protection treatments, the piers of the Katakhali 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, Corrpro 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