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Comparative study on various methods used for corrosion protection of rebar in concrete

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Abstract
Corrosion of reinforcing steel is one of the major causes of deterioration of reinforcement concrete structures worldwide. While several methods of corrosion protection of steel reinforcing bars in concrete have been developed, a unique method of corrosion protection is yet to be established. This paper experimentally compares the five commonly used methods of corrosion protection of rebar in concrete which are; high grade concrete, use of inhibitors in concrete, concrete surface coating, rebar coating and cathodic protection. Concrete cylindrical specimens with embedded rebar are exposed to alternate wetting and drying cycles in sodium chloride solution to accelerate corrosion of rebar for a stipulated period of 72 days/ 1722 hours. Corrosion monitoring is carried out by measuring half-cell potential of the specimens twice a day during the exposure period. At the end of corrosive exposure, pullout test is carried out on all specimens to determine bond strength. After the pullout test, mass loss in the rebar is determined for all rebars. All these parameters are compared with the control specimen which is unprotected and the relative advantages and disadvantages of all methods have been studied.

Keywords: Rebar, Corrosion protection, Alternate wetting and drying, Pullout, Mass loss

1. Introduction
Reinforced concrete is an extremely popular construction material that is used worldwide. While various materials may be used as a reinforcing material in the concrete, steel has been extensively used as the reinforcement for concrete structures from decades. However, steel reinforcement in the concrete is most susceptible to corrosion and therefore is one of the major problems civil engineers are facing today. Every engineer dreams to build a structure having good strength as well as better durability. Corrosion is one factor which affects the durability of structure and it causes serious damage when the structure is exposed to severe environment. Corrosion of reinforcing steel in concrete will reduce bond strength and steel cross section area and thus affects the serviceability and durability of concrete structures.

D.P. Minin (1979) study was for investigating the corrosion in a solution of sea salt by alternate wetting and drying process. Sea salt of 2% and 10% was used for this method. During 3 years (excluding Sunday and public holidays) the specimens were subjected to 750 wetting and drying cycles as 1 cycle per a day. Ping Gu and J.J. Beaudoin (1998) conducted the study on half-cell potential measurements in different cases. They gave the factors affecting the half-cell potential readings in different protection conditions such as usage of inhibitors, cathodic protection, epoxy coated bars, organic coatings, dense concrete cover etc. They summarized that more negative reading of potential is generally considered to indicate a higher probability of corrosion.

L.K. Aggarwal *et al.* (1999) [16] study was to develop the cost-effective better performing epoxy/phenolic interpenetrating polymer network (IPN) coating for the protection of steel reinforcement in concrete exposed to aggressive environment. Physicomechanical properties along with chemical resistance against some acids, alkalies, fertilizers, and water have been determined. Bond strength test, accelerated corrosion cycling test by weight change method, adhesion bend test have been performed to know the corrosion resistance behavior of IPN-coating. Moetaz M. El-Hawary (1999) [17] studied the bond strength characteristics of epoxy-coated bars were assessed using a series of pull-out tests on the specimens containing epoxy coated bars subjected to marine environment.

The specimens were divided in three groups. The effect of marine exposure conditions and duration on the bond strength of epoxy-coated bars in concrete and on the difference in bond strength between epoxy-coated and uncoated bars in concrete were investigated and assessed. The results of variation of bond strength with exposure duration, for the three types of exposure conditions were obtained.

M.M. Al-Zahrani *et al.* (2002) [12] study is to evaluate steel reinforcement corrosion and some physical properties of concrete specimens coated with two polymer-based, a cement-based polymer-modified, and a cement-based waterproofing coatings. G.T. Parthiban *et al.* (2008) [8] study was to analyze the use of magnesium alloy anode for the cathodic protection of steel embedded in concrete. Magnesium alloy anode, designed for three years life, was installed at the center of reinforced concrete slab, containing 3.5% sodium chloride with respect to weight of cement, for cathodic protection. Potential of the embedded steel and the current flow between the anode and the steel were monitored, plotted and analyzed. Chloride concentration of concrete at different locations, for different timings, were also determined and analyzed. The results have shown that the chloride concentration was found to decrease at all the locations with increase in time. The mechanism of cathodic protection with the sacrificial anode could be correlated to the removal of corrosive ions such as chloride from the vicinity of steel.

Marco Ormellese *et al.* (2009) [7] studied the inhibitive action of organic substances toward chloride-induced corrosion on carbon steel rebar in alkaline environment. In their study, about 80 organic substances were tested: primary and tertiary 3 amines and alkanolamines, amino acids, mono- and poly-carboxylates. Christopher L. Page and George Sergi (2010) [15] study was about the developments in cathodic protection applied to reinforced concrete. The study of the cathodic protection methods, impressed current cathodic protection (ICCP) method and sacrificial anode method was done. They concluded that during the past two decades, the application of CP to reinforced concrete has advanced rapidly to become a widely accepted technology for dealing with problems of chloride induced corrosion. They reviewed certain important features of this progress and an indication of some of the areas of current development.

2. Experimental Program

Experimental program was carried out in different stages.

1. Mix design.
2. Preparation of reinforced concrete specimens.
3. Applying corrosion protection measures to the specimens.
4. Exposure of specimens to corrosion environment.
5. Corrosion monitoring with half-cell potential measurements.
6. Performing pull-out test.
7. Determination of mass loss.

2.1 Mix Design

Mix design was performed according to IS 10262:2009. M20 grade of concrete is used for all the specimens except for high grade concrete specimens. M50 grade of concrete is used for higher grade concrete specimens.

Accelerated curing (IS 9013:1978) is the method performed for curing the cubes prepared. Accelerated curing is the procedure to obtain high early age strength in concrete. Concrete cubes were prepared using the mix design according to IS 10262:2009 and they were allowed for curing in accelerated curing tank (Figure. 1) at a maximum temperature of 100^0C for three and a half hour.

Fig 1: Accelerated curing tank

After three and a half hours of curing, the cubes were taken out of the tank and allowed for cooling in water at room temperature for two and a half hours. After two and a half hours of cooling, cubes were tested for compressive strength to know the grade of concrete.

2.2 Preparation of Reinforced Concrete Specimens

Cylindrical specimens with an embedded steel bar were casted in this study. The height and the diameter of the specimen were 200 mm and 100 mm, respectively. A standard reinforcing bar of 306 mm length and 12 mm nominal diameter of Fe 500 grade was used. These bars were kept immediately in the oil after they were rolled out from the manufacturing unit. Whenever casting was there the bars were taken out from oil and cleaned them properly with acetone to ensure that there is no oil on its surface. After proper cleaning, the weights and lengths are all the rebars were measured. As the lengths of bars are not equal from one to the other due to cutting errors at the manufacturing unit, it was essential to measure the lengths of the bars also.

3. Corrosion Protection Methodologies.

3.1 High Grade Concrete

M50 grade of concrete was used to prepare high grade concrete specimens.

3.2 Use of Corrosion Inhibitors

Inhibitor type: Water based organic corrosion inhibitor that works on the Bipolar Inhibition Mechanism.

Name of the inhibitor: EPCO®-KP-200

Manufacturer: Krishna Conchem Products Pvt Ltd, Mumbai

EPCO®-KP-200 is a hi-tech corrosion inhibitor system that works on the Bipolar Inhibition Mechanism (B. I. M.)®. This inhibits corrosion of steel in concrete at both the poles, cathodic & anodic simultaneously. EPCO®-KP-200 diffuses through the densest concrete to reach the corroding steel. The migration of EPCO®-KP-200 takes place over a prolonged period of time and hence this molecular layer shall continue to protect rebar by its constant presence.

Application Procedure

EPCO®-KP-200 was used as an admixture, by adding into wet concrete mix along with batch water during the mixing of cement, sand, aggregate before placement or pouring into transit mixer to impart corrosion protection to the embedded reinforcement. The batch water shall be calculated accounting for the quantity of EPCO®-KP-200 to be added at 2 kgs per cubic meter. Application procedure was given in the manual provided by manufacturer.

3.3 Concrete Surface Coating

Type of surface coating: Two pack polyamide cured air drying epoxy compound.
Name of the coating: Corroseal
Manufacturer: Krishna Conchem Products Pvt Ltd, Mumbai

Application Procedure

Corroseal base and curing agent were mixed in equal proportions by volume and allowed the mix to remain for 10 minutes before application. This mix was applied on the surface of concrete with 2 coats with in a time interval of 24 hours between coats. Figure. 2 shows the surface coated specimen.

Fig 2: Surface coated specimen

3.4 Rebar Coating

Type of rebar coating: Epoxy compound
Name of the coating: IPNET®-RB
Manufacturer: Krishna Conchem Products Pvt Ltd, Mumbai

Unique Advantages

Site based application. Rebar can be cut, bent or welded prior to the sandblasting and application of IPNet®-RB. The film has excellent corrosion resistance and mechanical strength properties, compared to neat epoxy systems.

Application Procedure

Rebar coating was prepared by mixing base which is epoxy compound and curing agent in equal proportions by volume for five minutes and allowed it to remain in the container for five minutes. The prepared mix was applied to the rebar using brush carefully and allowed it to cure for 48 hours minimum. Figure. 3 shows the rebars after application of coating.

Fig 3: Coated rebars

3.5 Cathodic Protection

For sacrificial anode method, aluminium metal was used as anode. The connection was given through a simple electric wire as shown in Figure. 4.

Fig 4: Sacrificial anode installation

One end of the wire is connected to the copper wire left outside the rebar and the other end is connected to the anode metal. A groove was given to the anode metal to tie the wire properly which is coming from rebar. A gap was maintained between concrete surface and anode. The electrolytic solution in this gap is able to transfer electrons easily between anode and rebar which can close the circuit.

For impressed current cathodic protection (ICCP) method, Carbon fiber reinforced plastic (CFRP) plates were used as anodes (Figure. 5). CFRP (Carbon Fiber Reinforced Plastic) is a composite material, consisting of various carbon fibers and thermosetting resins. Connection was given by connecting all the rebars at once, connecting to negative of DC source and all the anodes at once connecting to positive of DC source as shown in Figure. 6. Constant Current is used in this system.

Fig 5: CFRP Anode for ICCP

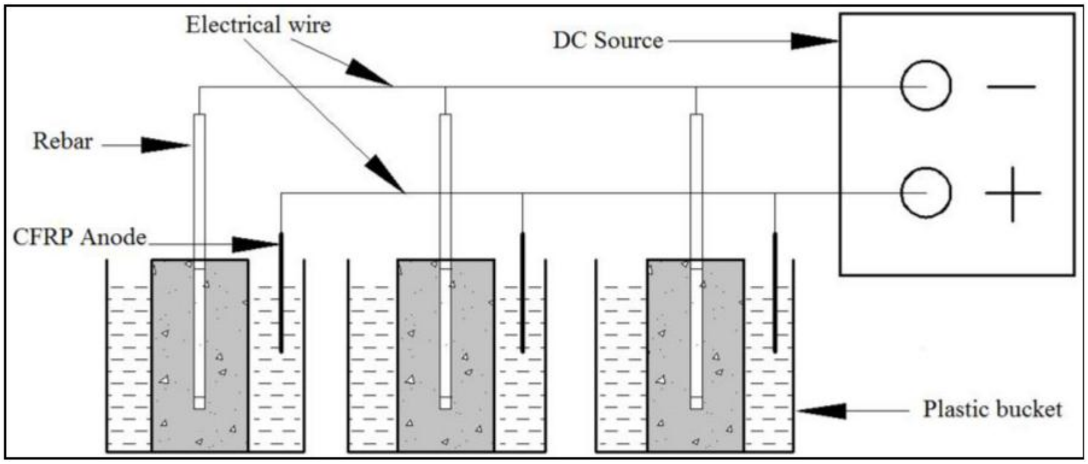

Fig 6: Impressed current cathodic protection installation

Current density of 0.9mA/cm2 was applied to each rebar from DC source. The specimens were kept in the plastic buckets with the salt water inside the buckets throughout the exposure period since it is an electrolyte which maintains the closed connection.

4. Corrosion Exposure

As the corrosion of rebar in concrete is a prolonged process, accelerated corrosion is the proper method to complete the study quickly. Different types of accelerated corrosion techniques are there for the corrosion exposure as follows (Bo Carlsson *et al.* 2006).

1. Continuous salt spray tests.
2. Alternating immersion of specimens in a salt solution followed by drying (Alternate wetting and drying).
3. Continuous exposure to atmospheres with corrosion promoting gases at moderately high humidity.
4. High humidity test.
5. Providing chloride to the concrete while preparation.

Alternative wetting and drying process was used for corrosion exposure in this study. It is an accelerated corrosion method to make the bars to get corroded in lesser amount of time. Alternative wetting and drying produces a corrosive environment of dense saline fog which produces severely corrosive conditions. This happens due to drying and evaporation of water in hot climatic conditions. The portion where this fog occurs there, salt is unable separate from rebar which is accumulated on its surface. After immediate wetting, the chlorides and water will react together to accelerate the corrosion process.

All the specimens were kept in 3.5% Aqueous NaCl solution which contains 3.5% salt as shown in Figure. 7

Fig 7: Specimens subjected to Corrosion Exposure

The specimen is fixed between the two plates shown in Figure 8. Maximum thickness of plates is taken as 25mm and minimum is 20 mm. Specimen is kept between the two plates and bolts of 12mm diameter and 300mm height are drawn into the holes provided to the plates. The bolts are tightened using a wrench so that the specimen is unmovable. The vertical portion of T-section is fixed to the lower jaws of UTM and rebar is fixed to the upper jaws of UTM.

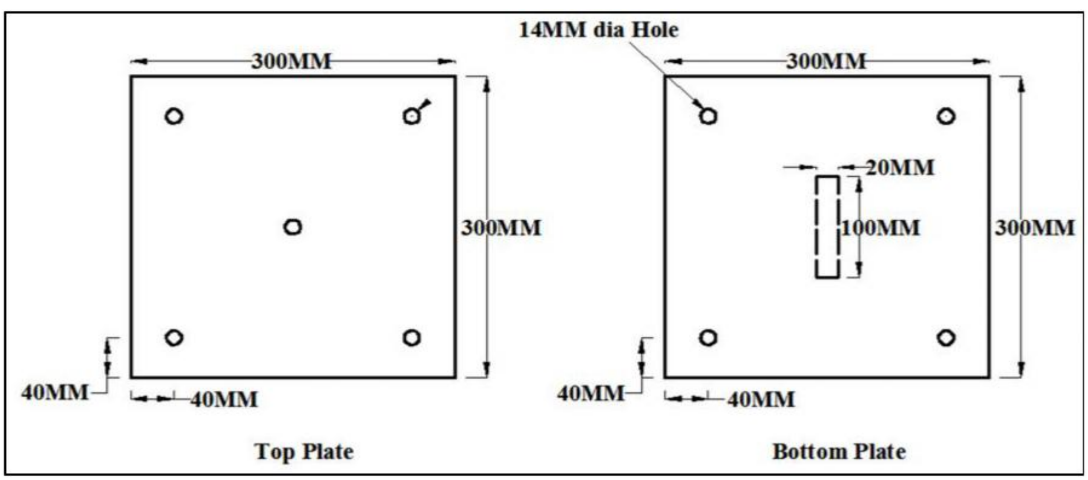

Fig 8: Plan: Pull-Out assembly

4.1 Procedure for Pull-Out Test

Fig 9: Fixing the vertical portion of bottom plate into the lower jaws of UTM

- The vertical portion of bottom plate is kept into the lower jaws of UTM as shown in Figure. 9. It is perfectly fit into the jaws.
- Before placing the bottom plate on UTM, the bolts are drawn at four corners of the plate and they are tightened using the nuts.
- On the top of bottom plate, the specimen is placed exactly at the centre of the plate.
- Another plate is kept on the top of specimen. The rebar of specimen passes through the central hole of the top plate. Bolts are also passed through the each hole at the corner of the plate.
- After placing the top plate on the specimen, the bolts are tightened with the nuts using the wrench. Now the specimen is stable and unmovable.
- Now the rebar is fixed into the upper jaws of UTM.
- The installed pull-out assembly is shown in Figure 10.
- After installation of pull-out assembly into the UTM, the gradual pull is applied on the rebar till the load reaches its ultimate value. This value is considered as ultimate pull-out load.

Fig 10: Installation of pull-out assembly

4.2 Mass Loss

After the pull-out, the Teflon tape from the rebar was removed and the rebars were cleaned properly with the use of wire brush and acetone to ensure that there is no visible rust on the surface of rebar. Apart from rust, the powder of concrete was also removed from the surface of rebar. Then the mass of rebar was measured on the weighing balance which was used to measure the initial masses of rebars.

5. Conclusions

Comparing the various corrosion protection methods following conclusions can be drawn:

- All the corrosion protections methods are effective with their relative advantages and disadvantages.
- HGC have shown best performance in providing bond between concrete and steel due to its material property which holds the bar so tight. It is clear that as the grade of concrete increases bond strength also increases according to IS 456. So, HGC is capable to maintain proper bond between concrete and rebar.
- Even though the grade of concrete is less for IN specimens unlike HGC, they have shown best behavior of protecting rebar from corrosion and providing adequate bond between rebar and concrete. So, for the structures where the grade of concrete is not allowed to keep more, corrosion protection using inhibitors is the best method since is requires only an admixture to use in concrete.
- Surface coated specimens have also shown positive results in protecting rebar from corrosion but not as effective as HGC and IN.
- Rebar coated specimens have shown best result in providing protection to the rebar from corrosion but failed to provide sufficient bond between concrete and rebar.
- ICCP has no standard protection current densities are available. Therefore obtaining the appropriate current density is a major task in the implementation of ICCP system.
- In SA system, since the issues of current density are not involved, it is easier to apply as compared to ICCP. However, there could be substantial loss of anode material that may need replacement down the line.

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