

Corrosion performance of coated reinforcing bars embedded in concrete and exposed to natural marine environment

P. Venkatesan^{a,*}, N. Palaniswamy^a, K. Rajagopal^b

^a Central Electrochemical Research Institute, Karaikudi 630006, India

^b AC College of Engineering and Technology, Karaikudi 630004, India

Received 1 September 2005; accepted 12 January 2006

Abstract

Corrosion behavior of mild steel plain bar embedded in concrete with 28 days compressive strength of 40 N/mm² exposed to natural marine environment at a location in the Gulf of Mannar was studied. This paper reports the results of 1-year study conducted on the reinforced concrete specimens exposed to three different levels. The performance of three different types of corrosion protection by specialty coatings to rebars, namely cement polymer composite, interpenetrating polymer network coating and epoxy coating was also evaluated periodically by measuring open circuit potential measurements and the results are discussed. Biofouling was predominant on completion of 3 months immersion. © 2006 Elsevier B.V. All rights reserved.

Keywords: Concrete corrosion; Mild steel rebar; Marine environment; Gravimetry; Biofouling

1. Introduction

The corrosion of the reinforcement bar (rebar) is the main cause of damage and early failure of reinforced concrete structures especially those located in aggressive marine and industrial environment. The reinforcement in all the structures provides a constructional security. Steel embedded in good quality concrete is protected by the high alkalinity of pore water, which in the presence of oxygen, passivates the steel. The loss of alkalinity due to carbonation of the concrete and the penetration of chloride ions to steel can destroy the passive film [1–4].

It is believed that reinforced concrete structures are durable and maintenance-free for the whole of its design life, approximately more than 60 years [5–7]. However, the corrosion of reinforcing steel in concrete exposed to aggressive environment affects the life of the concrete and thus has rapidly become a serious problem throughout the world. Parking structures, bridges, buildings, and other reinforced concrete structures exposed to marine and industrial environments are being severely damaged due to corrosion of reinforcing steel within periods as short as 10–20 years [8,9].

Organic coatings are a cost-effective way to protect metals. However, at defects or sites of damage in the coating, a local corrosion cell develops leading to coating breakdown [10]. Alkali generated at the cathode tends to inhibit anodic attack in these areas, but reduces the adhesion between coating and metal to zero, resulting in disbonding around the defect [11] or blisters near the defect [12]. The controlling factors in coating delamination have been extensively studied [13–16]. These experiments show the same reversal of polarity seen previously [17–19].

On the basis of the data, Asthana concluded that the IPN-coated reinforcing rebars have acceptable bond strength with concrete, and have better corrosion resistance than other commercially available treatment used for similar applications [20]. The economics of the treatment is quite attractive since treatment costs about 15–20% of the cost of steel. Hence it may be said that IPN-coated reinforcing steel bars fulfill the minimum requirements laid down in various standard specifications. Asthana concludes from the studies that the IPN-coated steel reinforcement rebars would have a more extended life in comparison to uncoated reinforcement.

The pH may become lowered if the concrete contains chlorides, sulphates, and other deleterious chemicals. These chemicals diffuse through the concrete and lower the pH value of the water in the pores of concrete. As a result, protective oxide

* Corresponding author. Tel.: +91 4565 227555/56/57/58/59; fax: +91 4565 227779/13.

E-mail addresses: p_venkat27@cecri.res.in, p_venkat27@gmail.com (P. Venkatesan).

film is pierced by these chemicals, which will then attack the reinforcement [21,22].

Abblas and Van London [23] reviewed the literature concerning the effect of chloride contamination on the corrosion of coated steel surfaces. Appleman [24], Heivig [25], Weldon et al. [26] and Flores and Starr [27] showed various correlations between level of chloride and premature coating failures. These investigators applied the contaminant (chloride) in known quantities to the steel surface and applied the coating shortly thereafter. Neaj and Whitehurst [28] used chloride contamination that remained in the micropits after sand blasting of steel surface for studying FBE coating performance. They found that in the presence of a pitted surface, chloride contamination could cause serious loss of performance in FBE coatings in hot cathodic disbonding and hot water tests. For underground coatings and other immersion coatings in critical applications, a maximum chloride level of 2 ppm was suggested [29].

It is generally assumed for steels without surface coatings that chloride-induced corrosion results from the breakdown of the passive film. In the presence of a passive film, it is believed that the corrosion process results from the electrostatic attraction between the positively charged metal surface and the negatively charged chloride ions [30]. It is believed that chloride ions react at areas where the passive film is discontinuous, damaged, or at heterogeneous sites on the steel surface. After initiation, the chloride ions are used as a catalyst for the liberation of iron ions, resulting in further corrosion.

The corrosion performance of steel reinforcement embedded in cementitious materials exposed to chlorides is a function of both the concrete and steel characteristics.

In this paper the corrosion behavior of mild steel reinforced plain rods and with three different types of coatings exposed to natural marine environment over a period of 1 year is presented.

2. Materials and methods

Mild steel plain rebar of diameter 16 mm and length 200 mm was used. The initial weight of the mild steel rebar specimens was recorded for gravimetric studies. 7/20 gauge wires were soldered to the MS rods for electrochemical studies. The reinforcement concrete specimens of dimensions 150 mm × 150 mm × 300 mm containing one control (uncoated) and three coated mild steel rebar rod were cast. The concrete mix proportion was 1:1.2:2.4. Ordinary Portland cement with river sand as fine aggregate and 20 mm stones and coarse aggregate were used. The water cement ratio used was 0.45. Identical specimens without reinforcing rods were cast and tested in the universal compression testing machine for obtaining compressive strength. Three coatings cement polymer composite coating (CPCC), interpenetrating polymer network coating (IPN) and epoxy coating (EC) was applied for an average thickness of 150 ± 25 μm.

For gravimetric methods, the concrete cubes were broken open after the specified time period and after immersing the rebar's in pickling acid for sufficient period, the weight of the reinforcement steel rods was taken and the corrosion rate was

estimated using the relationship:

$$\text{corrosion rate (mmpy)} = \frac{87.6W}{DAT} \quad (1)$$

where W is the weight loss in milligrams, D the density of the material in gm/cm³, A the surface area of the specimen in cm², and T is the time of exposure in hours.

For open circuit potential measurements a saturated calomel electrode having a wetted cotton tip was placed over the concrete surface and the potential was measured periodically between the reinforcement rod and the reference electrode using a multimeter.

The water-soluble chloride was estimated by volumetric method by preparing cement extract. The test solution was neutralized with diluted sulphuric acid (H₂SO₄) then titrated against standard silver nitrate (AgNO₃) using potassium chromate as indicator.

3. Exposure details

For the study of the reinforced concrete specimens in natural marine environment the unique facility available at the Offshore Platform and Marine Electrochemistry Centre (OPMEC), an unit of Central Electrochemical Research Institute (CSIR) situated at a distance of 2 km from seashore located in Gulf of Mannar at New Harbor, Tuticorin, India was made use of. The reinforced concrete specimens were tied using polypropylene wire and suspended from the platform of OPMEC unit. The specimens were positioned at three different levels identified as atmospheric, high tide and seafloor.

3.1. Atmospheric level (AL)

The reinforcement concrete specimens were positioned at the platform and exposed to typical natural marine atmosphere.

3.2. High tide level (HL)

High tide level refers to the depth at which the reinforcement concrete specimen was subjected to severe wave action of the sea. Due to this, the specimens were subjected alternate wet and dry conditions.

3.3. Seafloor level (SFL)

Seafloor level corresponds to the level where the submersed reinforcement concrete specimens were placed on the seafloor under the sea. This refers to a depth of approximately 9 m from the platform.

4. Results and discussions

4.1. Open circuit potential

4.1.1. Atmospheric level

The open circuit potential measured for the control (mild steel) as well as coated rods exposed to the atmospheric level as

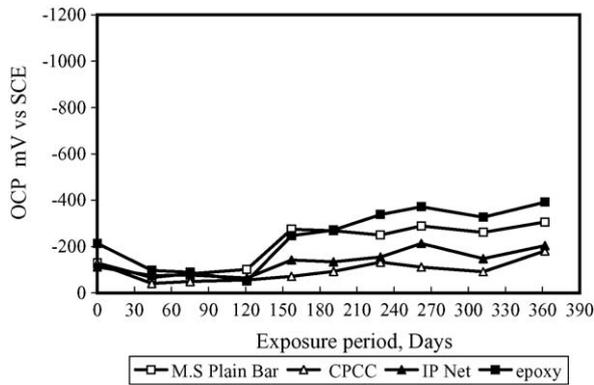


Fig. 1. Open circuit potentials of mild steel embedded in concrete exposed to atmospheric level.

described earlier is monitored periodically and the results for a period of 1 year is shown in Fig. 1. All the potentials are negative and shifts to the active side but within the threshold value of -270 mV versus SCE as per the ASTM C 876(3). The potential of mild steel plain bar and epoxy coated bar, at the instant of 157th day crossed the threshold value of -270 mV versus SCE. CPCC coated steel performed better than all other systems and the order of performance is given as below: after completion of 157 days, CPCC > IP net > epoxy > plain; after completion of 362 days, CPCC > IP net > plain > EC.

4.1.2. High tide level

Fig. 2 depicts the open circuit potential data collected for a period of 1 year in high tide level. All the coated and control rebar crossed the threshold potential limit of -270 mV versus SCE within 44 days of exposure indicating 5% probability of active corrosion of the reinforcement rods. Even though the control plain bar shows more active potentials than all the coated rebar at the initial time intervals, the control tends to have more active potential after 300 days of immersion and the overall trend of the potentials of all the rebar remains the same with steep fall in potential, i.e. more active at initial stages followed by a small rate of change of potential. CPCC coated steel performed better than all other systems and the order of performance is given as below: after completion of 44 days, plain > IP net > CPCC > epoxy; after completion of 362 days, CPCC > IP net > epoxy and plain.

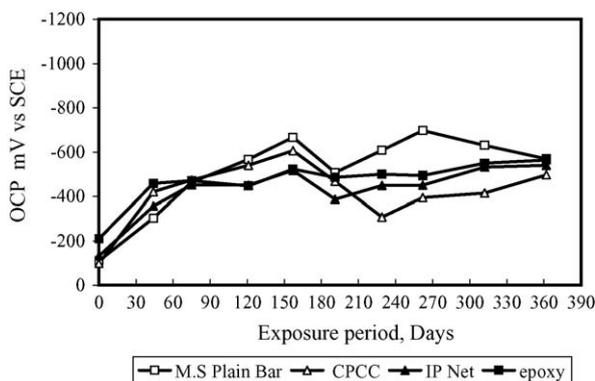


Fig. 2. Open circuit potentials of mild steel embedded in concrete exposed to high tide level.

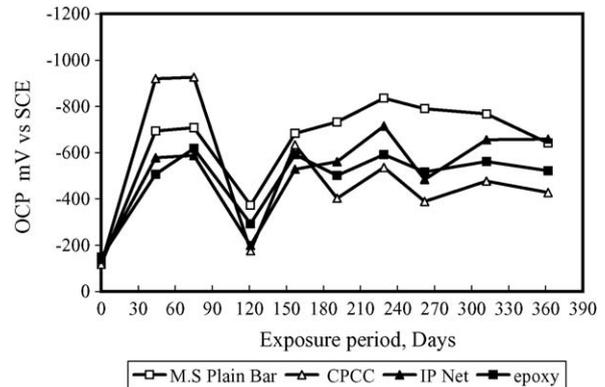


Fig. 3. Open circuit potentials of mild steel embedded in concrete immersed in seafloor level.

4.1.3. Seafloor level (SFL)

Fig. 3 shows the corrosion behavior of mild steel reinforced concrete without and with CPCC, IP net and epoxy coating in the seafloor level as observed by the open circuit potential measurements. As inferred from the figure, CPCC coated rebar specimen performs better than the other three specimens. Interestingly the biofouling studies have shown the absence of iron bacterial attachments in this level with only heterotrophic and manganese-depositing bacteria of almost equal populations (3.1×10^2 and 2.6×10^2), which remain unaffected, even after 8 months of exposure. Biofouling was predominant.

4.2. Weight loss (gravimetric) method

Table 1 shows the corrosion rate based on weight loss method for mild steel rebar control after completion of 1 year at various levels. At atmospheric level no corrosion, at high tide level the corrosion rate was 0.0087 mmpy and at seafloor level the corrosion rate was 0.0090 mmpy.

4.3. Linear polarization method

Table 2 shows the corrosion rate based on Linear polarization method for mild steel plain rebar, CPCC coated rebar, IP net coated bar and epoxy coated bar after completion of 1 year at various levels.

4.4. ac impedance method

Table 3 shows the corrosion rate based on ac impedance method for mild steel plain rebar, CPCC coated rebar, IP net coated bar and epoxy coated bar after completion of 1 year at various levels.

Table 1
Corrosion rate for mild steel rebar based on weight loss method

Level	Corrosion rate (mmpy)
Atmospheric level	0
High tide level	0.0087
Seafloor level	0.0090

Table 2
Corrosion rate (mmpy) based on linear polarization method

Level	Mild steel plain (control) bar	CPCC coated bar	IP net coated bar	Epoxy coated bar
Atmospheric	0.0001	0.000	0.0008	0.0013
High tide	0.0281	0.0066	0.0088	0.0101
Seafloor	0.0201	0.0011	0.0021	0.0033

Table 3
Corrosion rate (mmpy) based on ac impedance method

Level	Mild steel plain bar	CPCC coated bar	IP net coated bar	Epoxy coated bar
Atmospheric level	0.0130	0.0004	0.0007	0.0008
High tide level	0.0126	0.0008	0.0022	0.0011
Seafloor level	0.0196	0.0009	0.0021	0.0014

Table 4
pH and water-soluble chloride values

Level	pH value (initial value 13.2)	Chloride (ppm) (initial value < 100 ppm)
Atmospheric	11.07	1340.12
High tide	11.01	3254.58
Seafloor	11.06	2488.80

Table 5
Fouling community distribution pattern

Depth (m)	Community	Population intensity
Surface of the sea	Oyster	Dense
	Barnacle	Dense
	Ascidians	Sparse
Seafloor (7 m from the surface)	Ascidians	Dense
	Barnacle	Sparse
	Bryozoans	Scattered
	Mollusk	Scattered

Table 6
Biomass on concrete specimen

Depth (m)	Wet weight (g/dm ²)
Surface of the sea	40.40
Seafloor (7 m from the surface)	43.11

4.5. pH value and chloride content

Table 4 shows pH and water-soluble chloride value of the concrete specimens after 1-year exposure and immersion to natural marine environment.

4.6. Biofouling

Table 5 shows the pattern of distribution of fouling community on concrete specimens immersed in sea at various depths.

Table 6 shows the biomass on concrete specimen after completion of 8 months immersion, the concrete specimen immersed in bottom of the sea (7 m from the surface) registered relatively

higher biomass of 43.11 g/dm² (wet weight) while surface sample shows lower biomass of 40.4 g/dm² (wet weight).

5. Conclusion

5.1. Atmospheric level

5.1.1. ac impedance method

At atmospheric level CPCC coated rebar relatively performed well by giving less corrosion rate by impedance method after completion of 362 days exposure to natural marine environment. The order of performance is given as below:

CPCC > IP net > epoxy > control

The results of linear polarization method and open circuit potential technique followed the similar trend.

5.1.2. Gravimetric method

The corrosion rate mild steel plain bar was zero after 362 days of exposure to natural marine environment based on weight loss method. Visual inspection on coated rebar revealed that the CPCC, IP net and epoxy coating gave full protection during this period exposure/immersion.

5.2. High tide level

5.2.1. ac impedance method

At high tide level CPCC coated rebar performed relatively well by giving less corrosion rate by impedance method after completion of 362 days exposure to natural marine environment. The order of performance is given as below:

CPCC > epoxy > IP net > control

The results of linear polarization method and open circuit potential technique followed the similar trend.

5.2.2. Gravimetric method

Mild steel plain bar shown the corrosion rate of 0.0087 mmpy after 362 days of exposure to natural marine environment based on weight loss method. Visual inspection on coated rebar

revealed that the CPCC, IP net and epoxy coating were not damaged during this period exposure/immersion.

5.3. Seafloor level

5.3.1. Impedance method

At seafloor level CPCC coated rebar performed relatively well by giving less corrosion rate by impedance method after completion of 362 days exposure to natural marine environment. The order of performance is given as below:

CPCC > epoxy > IP net > control

The results of linear polarization method, open circuit potential technique followed the similar trend.

5.3.2. Gravimetric method

Mild steel plain bar shown the greater corrosion rate of 0.0090 mmpy at seafloor level after 362 days of exposure to natural marine environment based on weight loss method. Visual inspection on coated rebar revealed that the CPCC, IP net and epoxy coating were not damaged.

Acknowledgment

The author acknowledges the Director CECRI, Karaikudi who had given him the opportunity to work in the field of marine concrete corrosion.

References

- [1] ACI Committee 222, Corrosion of metals in concrete, ACIR-85, American Concrete Institute, Detroit, MI, 1985.
- [2] Z.P. Bazanth, Physical model for steel corrosion in concrete sea structures—theory, J. Str. Div., ASCE 105 (ST6) (1979) 1137–1153.
- [3] RILEM Technical Committee 60 CSC, Corrosion of steel in concrete, state of the art report, 1986.
- [4] C.L. Page, K.W.J. Treadaway, P.B. Bamforth (Eds.), Corrosion of Reinforcement in Concrete, Society of Chemical Industry, London, 1990.
- [5] F.E. Turnearsure, E.R. Maurer, Principles of Reinforced Concrete Constructions, John Wiley & Sons, New York, 1955.
- [6] Building Research Establishment, Durability of steel in concrete. Part I. Mechanism of protection and corrosion, BRE Digest 263 (1982) 1–8.
- [7] F.M. Lea, Chemistry of Cement & Concrete, Edward Arnold Publishers Ltd., London, 1956.
- [8] Proceedings of the International Congress of Navigation, London, 1923; Venice, 1931; Lisbon, 1949.
- [9] Seminar on pile foundations, corrosion detailing and ground anchors, Report IABSE, Madras, 1979.
- [10] J.E.O. Mayne, JOCCA 33 (361) (1950) 312.
- [11] H. Leidheiser, L. Igetoft, W. Wang, Prog. Org. Coat. 11 (1983) 19.
- [12] W. Funke, Prog. Org. Coat. 9 (1981) 29.
- [13] H. Leidheiser, M.W. Kendig, Corrosion 32 (1976) 69.
- [14] E.L. Koehler, M.W. Kendig, Corrosion 40 (1974) 5.
- [15] D. Greenfield, J.D. Scantlebury, J. Corros. Sci. Eng. 3 (2000) 5.
- [16] J.D. Crossen, J.M. Sykes, G.A.D. Briggs, J.P. Lomas, in: J.D. Scantlebury, M.W. Kendig (Eds.), Advances in Corrosion Protection by Organic Coatings, Electrochemical Society, 1995, p. 274.
- [17] M. Doherty, J.M. Sykes, Corros. Sci. 46 (2004) 1365.
- [18] B. Reddy, M. Doherty, J.M. Sykes, Electrochim. Acta 49 (2004) 2965–2972.
- [19] J.M. Sykes, B. Reddy, M. Doherty, Corrosion in 21st century, Manchester, J. Corros. Sci. Eng., submitted for publication.
- [20] K.K. Asthana, L.K. Aggarwal, R. Lakhani, A novel interpenetrating polymer network coating for the protection of steel reinforcement in concrete, Cem. Concr. Res. 29 (1999) 1541–1548.
- [21] Building Research Establishment, Durability of steel in concrete. Part I. Mechanism of protection and corrosion, BRE Digest 263 (1982) 1–8.
- [22] M.S. Khan, Corrosion state of reinforcing steel in concrete at early age, ACI Mater. J. 88 (1991) 37–40.
- [23] B.P. Alblas, A.M. Van London, Protective coating Europe (1997).
- [24] B.R. Appleman, J. Protect. Coat. Linings (1997) 68.
- [25] V.E. Heivig, Met. Finish. (1980) 41.
- [26] D.G. Weldon, A. Bochan, M. Schbiden, J. Protect. Coat. Linings (1987) 46.
- [27] S. Flores, T.L. Starr, J. Protect. Coat. Linings (1994) 76.
- [28] D. Neaj, T. Whitehurst, Chloride contamination of line pipe, Mater. Performance 34 (2) (1995) 47.
- [29] J. Paul, Inspecting and repairing concrete before lining, Protect. Coat. Europe (1996) 16.
- [30] D.A. Jones, Principles and Prevention of Corrosion, second ed., Macmillan, New York, 1995.