REPORT

Corrosion Performance of Epoxy Coated Rebar & Black Bar in Accelerated Aging Environment Simulating GCC Marine Exposure Conditions

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10-October-2017

Preface

This report presents the results of two years long study to find out corrosion performance of epoxy coated rebars (ECR) against mild black bars. Southern Exposure condition were applied to concrete blocks reinforced with ECR, epoxy coated rebars with controlled damage (ECRCD) and mild steel rebars, respectively. The project was carried out with collaboration of Qatar Steel and Center for Advance materials at Qatar University. Qatar steel is determined to find out the solution for reinforced corrosion that has caused severe durability problems to the infrastructure in Gulf area including Qatar. QCoat a section of Qatar Steel developed ECR to counter the corrosion related problem to rapidly developing Qatar infrastructure. Center for Advance Materials at Qatar University is stat-of-the-art laboratory for materials agreed to test the durability of these ECR in concrete. The results show that ECR performed better than mild steel rebars in accelerated corrosion environment. It is concluded that ECR could withstand high concentration of chloride ions where mild steel bar would corrode severely.

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October 10, 2017

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1 Introduction

Arabian Peninsula has emerged as the leading construction market in the Asia and particularly in Middle East. The reinforced concrete is the typically used construction material to build the civil engineering structure likes harbors, bridges, multistory buildings and industrial silos[Al-Tayyib. et al., 1989]. Although concrete is most economical and suitable construction material having excellent adaptability to the architect of structures. However, in last few decades its durability has become a major challenge to construction industry. The corrosion of steel bars in concrete is main degrading phenomena in reinforced concrete, it could spall the cover and reduce the cross sectional area of bars to make the structures either not safe to be in service or in other cases causes the collapse of the structure[Broomfield, 2006]. The structures in Arabian Gulf suffers very aggressive environment of high temperature, high relative humidity and high chlorides ions in atmosphere. In industrial zones carbonation of concrete is also one of the causes of degradation[Al-Khaiat et al., 2007]. Once the corrosion of steel bars is initiated, the rust products distress the concrete around steel bars as the volume of iron rust is up to 10 times the volume of steel itself. That causes the concrete cover to fall off and loss in steel cross section which is direct loss in the strength of reinforced concrete. Qatar Steel as the major manufacturer of structural steel rebars in Qatar, has responded to the need of durable and corrosion free reinforcing bars in concrete by developing and producing the epoxy coated rebars (ECR) at its joint venture company Qatar Metals Coating, in Mesaieed Industrial City. To evaluate the performance of ECR in comparison with black bars (BB) a comprehensive two fold experimental plan is launched with the help of Center for Advance Materials (CAM) at Qatar University. The plan comprises on laboratory scale testing and large scale field trials at real marine environment. This report covers the laboratory scale testing and presents the experimental results of accelerated corrosion tests on concrete blocks reinforced with mild steel black bars (BB), ECR and epoxy coated rebars with controlled damage (ECRCD). The accelerated corrosion tests were performed by submerging the concrete samples for two years in NaCl- solution (i.e. seawater) at 38 to 52°C temperatures and relative humidity conditions simulating actual climatic conditions of Qatar. Results of electrochemical tests show that the durability of reinforced concrete structures could be enhanced by using epoxy coated rebars. After 2 years of submergence the black rebars were severely corroded while the epoxy coated rebars without any damage and with controlled damage performed exceptionally better with no breakdown of epoxy layer at steel surface.

2 Significance of Study

It is estimated that around 20,000 tons of construction and demolition (C&D) wastes are produced daily in Qatar [Al-Ansary and Iyengar, 2013]. These wastes are generated by the demolition of concrete structure that could not fulfill their service mainly due to the corrosion of reinforcing bars in concrete. The infrastructure in Qatar and the Persian Gulf suffers sever environment of Cl^- ions in atmosphere especially near seashores. When ingress in concrete pores the Cl^- ions destroy the passive layer at steel surface and corrosion process starts. The remaining structural life of concrete structures are drastically reduced when there is sever corrosion of steel rebars. To avoid this durability issue ECR has been in use since 1970's in United States. Since durability due to corrosion is main degrading phenomena in Qatari Infrastructure, use of epoxy could enhance the service life and reduce the repair cost of reinforced concrete structure, hence will have a direct bearing on the economy of country. Several indicative tests were performed which could help to relate the concrete quality to corrosion initiation or propagation in real structures.

3 Experimental Plan

Nine (09) concrete block samples of $300mmx230mmx70mm$ were prepared with a U shaped bended steel bar in it. The schematic of samples geometry is given in Figure-1. The Table-1 shows the details of the concrete blocks with type of steel bars. Three samples were cast for each combination for comparison purposes. The forming of U shape bent was provided to observe the effect of induced stress on corrosion behaviors.

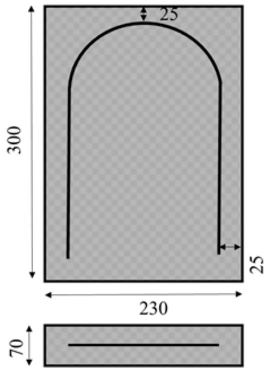


Fig. 1. Sample geometry with U shaped steel bars. All dimensions are in mm.

Table 1. Cast samples and their designations.

Sr. No.	Type of Steel Bar	Sample Designation
1	Black Bars (Mild steel)	BB-1
2	Black Bars (Mild steel)	BB-2
3	Black Bars (Mild steel)	BB-3
4	Epoxy Coated Rebar	ECR-1
5	Epoxy Coated Rebar	ECR-2
6	Epoxy Coated Rebar	ECR-3
7	Epoxy Coated Rebar with Controlled Damage	ECRCD-1
8	Epoxy Coated Rebar with Controlled Damage	ECRCD-2
9	Epoxy Coated Rebar with Controlled Damage	ECRCD-3

4 Materials

4.1 Steel

The chemical and physical properties of the epoxy coated rebars black rebars are given in Table-2 and Table-3, respectively.

Table 2. Chemical Composition of mild steel bars.

%C	%Mn	%Si	%P	%S	%V	%Cu	%Ni	%Cr
0.27	0.72	0.15	0.01	0.02	0.01	0	0.02	0.02

4.2 Concrete Composition

The mixture proportion of C40 concrete used is given in Table-4. The mixture is typically used in the concrete infrastructures in Qatar.

Table 3. Concrete mixture proportion.

Material	Prop. Kg/m3	Density SSD	Voulme Ltr	Absop.	Moist.Cor. Kg/m3	Final prop. Kg/m3
Cement SRC	380	3.15	120.6			380
Water	160	1	160		17.8	178
Aggregate 20 mm	580	2.81	206.4	0.7	4.06	576
Aggregate 10 mm	595	2.8	212.5	0.8	4.76	590
Qatar sand	745	2.65	281.1	1.2	8.94	736
Admixture 1	3.5	1.05	3.3			3.5
Air Conetent	-		15			
Total	2463.5		999			2463.5

5 Accelerated Aging Conditions

After curing by submerging in water for 28 days, the samples were placed in to the simulated Qatar and GCC corrosive environment of seawater in a salt spray chamber, as shown in Figure-2. The cycles of three (3) days heating and drying at a target temperature of 52°C was applied. This was followed by fours (4) days of ponding under seawater at 16 -27°C, these cycles continued for twelve (12) weeks. After initial cycles the samples were then submerged for continuous pounding under seawater at target of 32°C for next 12 weeks. This 24 weeks cycle is repeated 4 times for a total test period of 96 weeks (i.e.2 years).

With these wetting and drying cycles the chloride penetration in concrete is ensured. The water penetrates into the concrete pores transporting Cl^- ions with it during pounding of four days. It evaporates during drying periods leaving behind the Cl^- ions. This increases the chloride ions concentration at concrete surface. The diffusion process would help these ions to reach the steel concrete interface. After a certain level of concentration is achieved at steel concrete interface, the passive layer at steel surface is broken and corrosion is initiated.

(a) Salt spray chamber **(b)** Samples in Salt Spray Chamber

Fig. 2. Samples under accelerated aging conditions

6 Results and Discussion

6.1 Concrete Resistivity

Concrete resistivity is a measure of concrete quality, it also roughly related to the risk of corrosion. Less the value of concrete resistivity, larger would be the risk of corrosion to occur as flow of iron ions freed form steel rebars would find it easy to travel through concrete to react with OH- ions produced during reduction reaction of oxygen in half cell of corrosion process. The resistivity is measured by four point Wenner Probe. In this study Giatec® Resistivity Meter was used to measure the concrete surface resistivity in laboratory as shown in Figure-3. The device measures the concrete resistance of electrical charge transmitted by external electrodes and potential difference by central two electrodes. This is converted into the resistance Ohm, and then this resistence is converted to resistivity as below,

$$\rho = 4a\pi V/I \tag{1}$$

Where rho concrete resistivity in $Ohm - cm$, a is the distance between the electrodes. Figure-4 shows the resistivity values for concrete samples after two years of submergence in sea water. The chloride ions ingress through concrete pores and with available electron in Cl^- the conduction to electric charge through concrete increases. The minimum resistivity observed was 5024 $Ohm - cm$ while maximum was 12362 $Ohm - cm$ with an average of 7670 $Ohm - cm$ over nine samples. These values are compared with the values given in Table-4, which relate the resistivity to probability of corrosion risk suggested by different researcher from open literature[Song and Saraswathy, 2007]. It is observed that most of concrete blocks have such resistivity values at which the corrosion risk is ‘High’ or ‘Very High’. The concretes in marine environment generally have higher conductance to charge transfer due to the presence of Cl^- and water, and hence the risk of corrosion would be higher.

(a) **(b)**

Fig. 3. Schematic view of set up and concept of measurement. Right hand side shows the real time measurement Giatec® Resistivity meter.

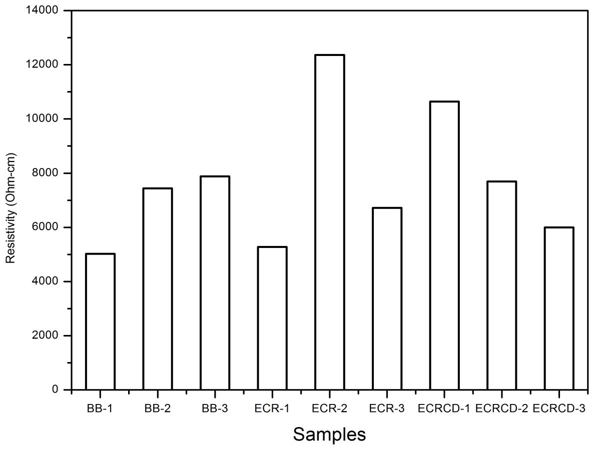


Fig. 4. Concrete resistivity measured at concrete samples after 2 years of submergence in seawater.

It should be noted that concrete with a compressive-strength of $40MPa$ could absorb very large quantities of chlorides by diffusion process through seawater especially at splash zone where wetting and drying cycles are encountered. The chloride concentration found to be very high than normally depicted as threshold values for corrosion initiation. The threshold value of chloride may have achieved much earlier than 2 years.

6.2 Chloride Profiling

The chloride ion (Cl^-) contents in concrete blocks at different depths starting from top concrete surface till the steel surface that is 25 mm depth were measures. The BS 1881 : Part-124 [1998] standards were followed to obtain these chloride profiles. The results are presented in Figure-5. The general trend for Cl^- concentration along the depth is that it decreases from its maximum value at the surface it the middle of concrete element. As the concrete was porous thickness of block was $5cm$ only (Is it right, as cover thickness is $25mm$) the chloride profile is almost constant throughout the depth till steel surface. The

Table 4. Corrosion risk related with concrete resistivity expressed by different researchers. [Song and Saraswathy, 2007].

Resistivity (Ohm-cm)	Corrosion Risk
> 20,000	Negligible
10,000 to 20,000	Low
5,000 to 10,000	High
< 5000	Very High

Cl^{-} ions concentration when passes a certain threshold value, it depassivates the steel corrosion. The values provided in profiles in Figure-5 are the percentages of total weight of sample used for BS 1881 : Part-124 [1998] standard test.

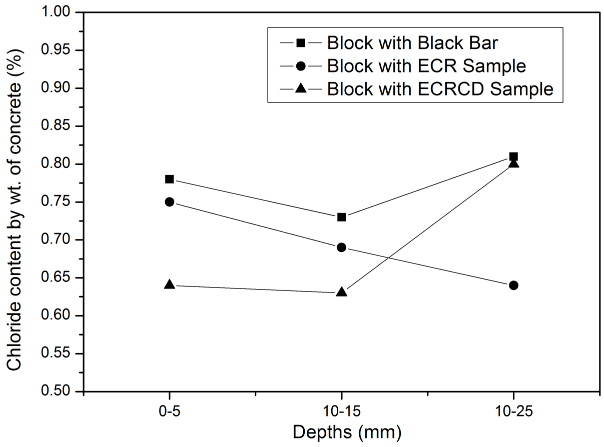


Fig. 5. Chloride profile in concrete blocks.

According to Broomfield [2006]), 0.4% of chloride by weight of cement is the threshold value for corrosion to be initiated. Some other researcher like Funahashi [1990] suggests Cl- threshold of 0.17% by weight of cement. While a threshold of 0.2% and 0.25% used by other researchers [Glass and Buenfeld, 1997]. Mostly, the chloride threshold are mentioned in percentage of weight of cement in the concrete sample. The risk of corrosion of steel bars increases with the increase in chloride ion concentration by weight of cement. The Table 5 provides the threshold Cl- concentration with respect to the total mass of concrete samples used for tests [Broomfield, 2006]. For a high risk of corrosion chloride concentration is suggested as 0.14% by weight of concrete sample. The concretes blocks studied have chloride concentration at least 6 times higher than 0.14% by weight of concrete samples. Near steel surface in blocks test have chloride concentration is at least 0.64%. From Figure 5 it is observed that two samples have chloride concentration of above 0.80% near steel surface. Darwin et al. [2009] have observed the chloride threshold for epoxy coated rebars, galvanized rebars and mild steel rebars as shown in Figure 6.

It should be noted that concrete with a compressive strength of 40 MPa could absorb

Table 5. The risk of corrosion with % chloride by mass of cement and mass of concrete sample. [Broomfield, 2006]

% Chloride by mass of cement	% Chloride by mass of sample (concrete)	Risk level.
< 0.2	< 0.03	Negligible
0.2-0.4	0.03-0.06	Low
0.4-1.0	0.06-0.14	Moderate
> 1.0	> 0.14	High

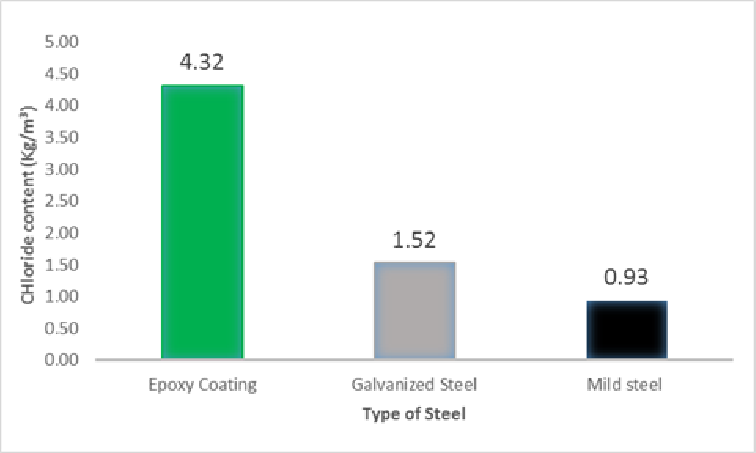


Fig. 6. Threshold value for different types of steel bars. [Darwin et al., 2009]

very large quantities of chlorides by diffusion process through seawater especially at splash zone where wetting and drying cycles are encountered. The chloride concentration found to be very high than normally depicted as threshold values for corrosion initiation. The threshold value of chloride may have achieved much earlier than 2 years.

6.3 Half-Cell Potential

Half-cell potential (HCP) of reinforcing steel bars is an indicator of corrosion initiation, with HCP the active steel bars with corrosion and passive steel bars with no corrosion could be identify. The commercially available half-cell measuring device called Giatec® was used to measure HCP, which follows ASTM C876-09 [2015].

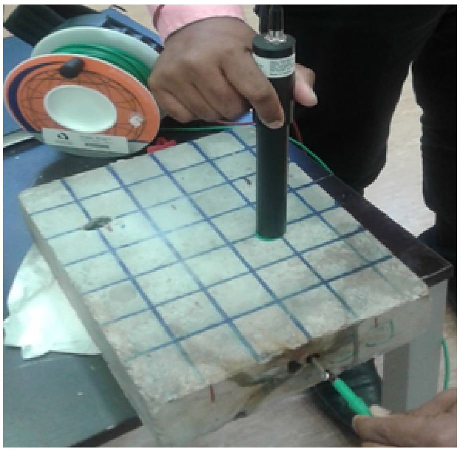
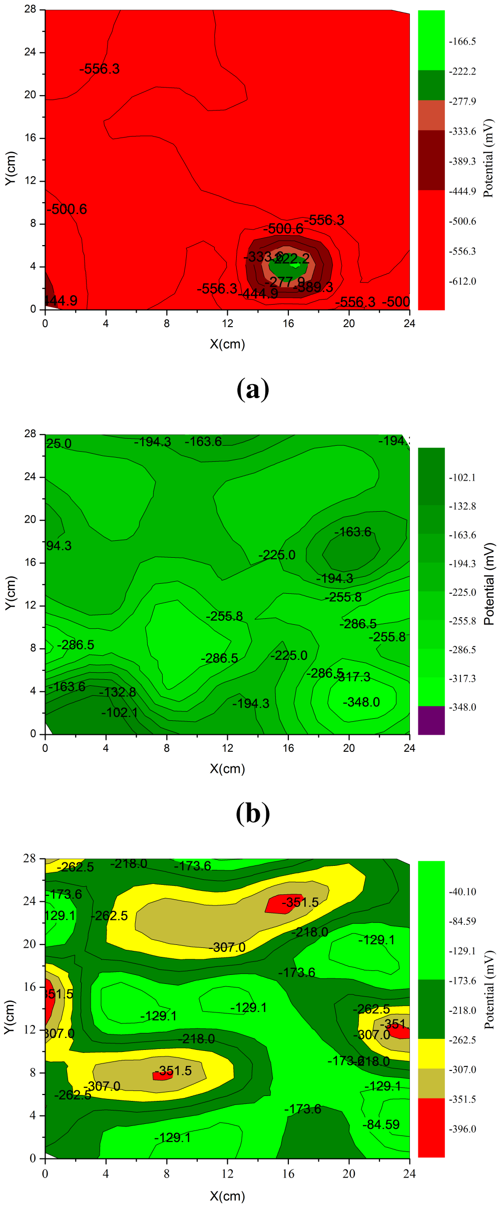


Fig. 7. Measurements on concrete blocks

Giatec® uses copper/copper sulfate (CSE) reference electrode to measure the half-cell potential of steel bars embedded in concrete blocks. A hole was drilled in blocks with black steel bars (Figure-7) and a chip of concrete was remove from one corner for epoxy coated steel bars. The concrete block was divided into small grids of $4cmx4cm$ to get half-cell potential contour on surface of concrete block. Figure-8 shows the contour mapping of one surface of BB-3. The open circuit potential (OPC) for blocks with black steel bars was above $-600mV/CSE$, which is according to ASTM C876-09 [2015] standards is in the range with 100% probability of corrosion on steel bars. Whole surface of the concrete block gave potential above $-550mV/CSE$, corrosion products were visible at surface, especially at surface just above the bent portions. The half-cell potentials measurements at ECR and ECRCD resulted in potential in the range of $-200to-350mV/CSE$ and shown in Figure-9. Which shows that the steel bars were not in active state and chloride concentration have not destroyed the epoxy coating. According to ASTM C876-09 [2015] the probability of corrosion at these potential is low. The HCP of ECR's is not possible to measure until the epoxy is removed and a direct connection is established at steel surface. The potential of epoxy coated controlled damaged steel bars suggested that small damage to surface could not initiate the corrosion process. The potential of these bars were also less electronegative than those of black steel bars as shown in Figure-10.



(a)

(b)

(c)

Fig. 8. Half-cell potential of a) bb-3, b)ECR-3 c)ECRCD-3

6.4 Tafel Plots

Tafel experiments were performed to obtain the polarization curves ($LogIvsE$ curves) and hence the corrosion current density (I_{corr}). The rebars were polarized $200mV$ from PC by using Gamry® Potentiostat. The three electrodes (working electrode (WE), counter electrode (CE) and reference electrode (RE)) set up as shown in Figure-10 was used to perform these experiments. A polarization is obtained and extrapolated to get the $Icorr$. The curves for black steel bars are shown in Figure-12. The linear polarization resistance (LPR) (R_p) curves are shown in Figure-11, a small polarization of 20 mV was applied

Table 6. Half-cell potential values for corrosion conditions.

OPC values		**Corrosion conditions**
mV vs. SCE	**mV vs. CSE**	**-**
less than-426	less than-500	Severe Corrosion
less than-276	less than-350	High (higher than 90% risk of corrosion)
-126 to -275	-200 to -350	Intermediate corrosion risk
higher than -125	higher than -200	Low (10% risk of corrosion)

from OPC to obtain these curves. The polarization resistance is an indication of how much corrosion has been going on steel surface. It is the slope of $IvsE$ curves as shown in Figure-12. R_p could be calculated from Eq.2, and instantaneous corrosion current density is further calculated from Eq. 3.

The constant B in Equ. 3 and Equ. 4 is Stern-Geary constant depending upon β_a@ and β_c@ which are anodic and cathodic Tafel constants, respectively. These parameters could be calculated from Tafel Polarization curves in Figure-12. It is important to note that the ECR and ECRCD were not able to be polarized since the epoxy coating was intact throughout the rebars and current is not able pass at all. The results of I_{corr}, R_p, β_a and β_c are presented in Table-8. The corrosion current at BB-2 according to Tafel polarization curves is 1.59 uA/cm^2 while in BB-3 it is 0.80 uA/cm^2. The corrosion current density is in the range that falls in 'moderate to high' or 'very high' corrosion rates on steel bars as depicted in Table-9. The loss in cross section could be measured form Eq. 5 below.

$$R_p = \frac{\Delta E}{\Delta I} \tag{2}$$

$$i_{corr} = \frac{B}{R_p} \tag{3}$$

$$B = \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)} \tag{4}$$

Where I_{corr} is the corrosion current intensity, in A, A is exposed surface area of the reinforcing steel in cm, E.W is the equivalent weight of steel, and d is the density of the reinforcing steel, in $g/cm3$. The corrosion rate at black steel bars are presented in Table-8, corrosion rates on ECR and ECRCD are possible to calculate and could be considered as zero corrosion rate.

$$Corrosionrate(\frac{mm}{year}) = \frac{3272 I_{corr} E.W}{dA} \tag{5}$$

The samples were broken after these electrochemical tests. The U bent portion of BB-1, BB-2 and BB-3 were severely corroded as shown in Figure 13 and Figure 14. On the other hand zero corrosion was observed on the ECR and ECRCD.

Table 7. Corrosion parameters from LPR and Tafel Experiments

	Corrosion Current		**Tafel Slope**		**Corrosion rate**	
Sample	**Icorr**		β_a	β_a		
	μA	μA/cm2	mV/dec	mV/dec	μm/year	mm/year
BB-2	369	2.94	450	420	0.6854	0.000685
BB-3	124	0.99	440	415	0.2303	0.00023

Table 8. Corrosion current vs. condition of the rebar [Song and Saraswathy, 2007]

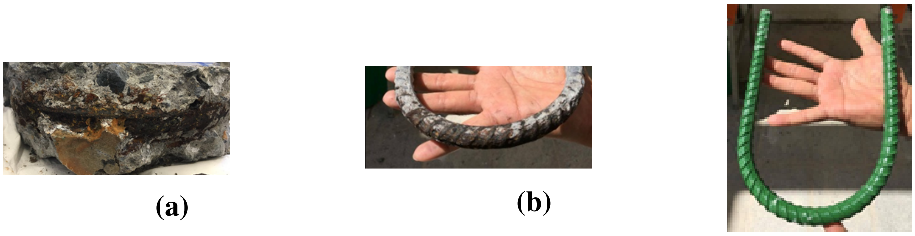
Corrosion Current (Icorr)	**Conditions of rebar**
<0.1 μA/cm2	Passive condition
0.1-0.5 μA/cm2	Low to moderate corrosion
0.5-1.0 μA/cm2	Moderate to high corrosion
>1.0 μA/cm2	High corrosion rate

6.5 Knife Test for Epoxy Coating

Adhesion of the ECR and ECRCD was tested in accordance with the knife-peel test Ontario Ministry of Transportation [1993]. It is recommended to apply two cuts in X shape of approximately 9*mm* in length. In this test, an adhesion number from 1 through 5 is assigned to each sample depending upon the condition of epoxy coating in Table-10. The epoxy coating of ECR and ECRCD were intact strongly, no change in color to the coating was observed after 2 years of submergence. The adhesion number of 1 was observed in all the tests. It was hard to cut through the epoxy coating. The steel surface was shining underneath the epoxy coating and no corrosion was going on.

Table 9. Adhesion number for epoxy coating [Ontario Ministry of Transportation, 1993].

Adhesion Number	**Description of Tested Area**
1	Unable to insert blade tip under coating
2	Total rea of exposed steel <2mm2
3	2 mm2 <total area of exposed steel> 4mm2
4	Total area of exposed steel >2mm2
5	Blade tip slides easily under coating, levering action removes entire section (approximately 40 mm2) coating



(a) **(b)** **(c)**

Fig. 9. Visual Inspection of concrete blocks with ECR and ECRCD

7 Conclusions and Recommendations

In this study the performance of epoxy coated rebars and black rebars was evaluated by putting reinforced concrete blocks in seawaterof two years. The main conclusion of this study is that epoxy coated rebars could withstand the heavy attack of chloride ions. After 2 years of submergence in seawaterthe coating was not damaged. Meanwhile the chloride concentration is observed to be 0.80 % of concrete sample weight in BS 1881 : Part-124 [1998] tests, which is much higher than the threshold for corrosion initiation in case of mild steel bars. [Darwin et al., 2009]) have observed the chloride threshold value for epoxy coated rebars is two to three time higher than galvanized or mild steel bars respectively. Concrete resistivity suggested that the corrosion risk very high in these block of concrete after 2 years of submergence. Further Half-cell potential of black bars (BB) was below $-600 mV/CSE$, while for ECR and ECRCD it was around -100 to -350mV/CSE which suggests passivity or no corrosion potential. Tafel plots and LPR values also suggested very high corrosion rates on BB-2 and BB-3, while no corrosion current was observed at ECR and ECRCD. Furthermore, as epoxy is insulator, no polarization could be applied to these rebars. The high corrosion rate at black bars will reduce the cross sectional area, the rust formed is up to 10 times more voluminous that steel itself and will cause the delamination of concrete cover. These results show that such problem would not exist in epoxy coating steel bars. Hence, as far as durability is concerned these epoxy coated steel rebars perform exceptionally better in aggressive marine environment than black steel bars. The bond between concrete and epoxy coated rebars is addressed by maintaining increased development length in rebar detailing while construction.

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