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Performance Evaluation of a Commercial Polyurethane Coating in Marine Environment

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A material evaluation study has been carried out to determine corrosion behavior of a commercial polyurethane coating system (Souplethane 5) in the marine environment. The coating system is solvent free, two-component polyurethane protective coating. The performance of the coating on steel and rebar concrete was evaluated by conducting different types of tests which include atmospheric exposure, immersion in 5% sodium chloride solution, exposure to splash zone in seawater, salt fog, sabkha soil burial, and electrochemical tests, which include potentiodynamic polarization and AC impedance measurements. Uncoated, coated, and coated scribed specimens were used in each study. In general, the coating showed good corrosion resistance in marine environment. However, the coated samples, when subjected to break under applied compressive load, showed partial or complete detachment from the substrate, e.g., steel and rebar concrete. This appears to be the major drawback of the coating while applying on steel and concrete structures.

Keywords AC impedance, atmospheric exposure, concrete and steel structure, electrochemical polarization, polyurethane, sabkha soil test, salt fog test, seawater immersion test

1. Introduction

For a lining system to be considered as suitable corrosion protection system, the lining must expose little or no metal surface to the environment, while also being resistant to environmental, mechanical, and chemical damage throughout its service life. The primary lining systems, which have been widely used worldwide and met the requirement of potable water services, include cement-mortar, solvent-borne amine based epoxy, 100% solid epoxy, and 100% solid polyurethane. Among the above systems, however, the selection of a particular lining system is a difficult task owing to various attributes which include coating properties, surface preparation requirements, application parameters, resistance to environmental attack, economics, and worker safety.

100% solid epoxies and 100% solid polyurethanes have gained substantial interest in recent years because of environmental regulations. They do offer the additional benefit of better safety and environmental parameters when compared to the solvent based materials. Recently, the performance evaluation of 100% solid epoxy (fusion-bonded epoxy) coatings has been carried out (Ref 1, 2). The coatings have showed excellent barrier properties with strong adhesion to the surface. 100% solid polyurethane coatings which usually consist of two components: one isocyanate-rich solution and one polyol-rich solution are formed when the two components are combined, and a rapid and exothermic chemical polymerization reaction takes place. In the past, polyurethane coating and lining systems were not considered as safe as epoxies because of the toxicology of the resins (polyols and especially isocyanates). The main hazardous pre-cursor of polyurethane is an isocyanate monomer. While there are many different types of isocyanates available in the market, most isocyanates used today in ANSI/NSF 61 approved polyurethane systems are of the MDI (diphenylmethane di-isocyanate) type. In these lining systems, polymeric MDI and special formulating technology are also adopted to further reduce the level of isocyanate monomer in the finished system. As a result, the polyurethane systems are in fact safer to use compared with most epoxy systems. 100% solid polyurethane coatings are used to protect many different structures today, such as storage tanks, oil and gas pipelines, water and wastewater, bridges, ships, and other facilities (Ref 3-5). The products have been effective because of their outstanding life expectancy and performance, resistance to aggressively corrosive environments, high abrasion resistance, fast application, low- and cold-temperature-curing capabilities, strong adhesion, unlimited film build, and compliance with the most rigorous regulations on volatile organic compound (VOC) emissions.

The Saudi Arabia's Saline Water Conversion Corporation (SWCC), the largest producer of desalinated water in the world, produces more than 1 billion m^3 of water through its 30 plants located along the Arabian Gulf and Red Sea coasts (Ref 6). Its vast infrastructural facilities are exposed to the aggressive marine environments. The present article describes the evaluation results of commercial polyurethane coating, Souplethane 5, under marine environments. The aim of the investigation is to evaluate the corrosion behavior of coating to find application on structural components exposed to marine environments.

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The coating subjected to evaluation is claimed to have strong adhesion to both concrete and steel substrate (concrete >3 MPa, steel >10 MPa), and provide excellent resistance to corrosion and aggressive chemicals (Ref 7). It is resistant to high temperature (up to 140 °C), thermal shock, mechanical abuse, such as abrasion, impact and vibrations, UV aging. The coating is further claimed to have wide acceptance and be providing protection solutions for many sectors, such as oil refining, gas and petrochemical processes, water and sewage, power and desalination, mining, health and pharmaceuticals, food, real estate and housing, and other industrial and operational segments. The coating is approved for use with potable water and in the food processing industry.

Fig. 1 Photograph of the test samples

Fig. 2 Photograph of the test samples after exposure to atmospheric test

2. Experimental

2.1 Coating

The Souplethane 5 is a high performance solvent free, two-component polyurethane protective coating. The coating is highly crosslinked to create a hard and dense membrane. The coated steel and concrete samples used for the evaluation were commercially obtained. The coating was applied as per the coating manual by a professional coating applicator.

3. Experimental Methodology

3.1 Testing Material

The details of the test specimens, obtained commercially, are as follows:

Steel specimens	Diameter × length of the mild steel rods = 20 × 80 mm
Concrete specimens	Diameter × length of concrete specimens = 35 × 70 mm
	Diameter × length of the rebar = 10 × 75 mm
Coating thickness	The coating was applied in two coats to achieve a 2-mm-thick film.

3.2 Testing of the Coating

The photograph of the coated steel and rebar concrete samples (both scribed and unscribed) along with uncoated steel and rebar concrete samples to be subjected to different type of testing is shown in Fig. 1. The performance of the coating was evaluated by conducting the following tests:

1. Atmospheric exposure tests [ASTM designations: G7-89 and D-1654-79a (Re-approved 1984)].
2. Immersion tests [ASTM specifications: G20-88 and G31-72 (Re-approved 1990)].
3. Salt fog tests [ASTM B117-90].
4. Tests in Sabkha soil [ASTM designation: G19-88].
5. Potentiodynamic polarization tests [ASTM G59-78].
6. AC Impedance tests.

3.2.1 Atmospheric Exposure Tests. The coated steel and rebar concrete samples (both scribed and unscribed) along with uncoated steel and rebar concrete samples were exposed to open atmosphere. The samples were weighed and subsequently fixed on a panel which stood on a heavy metallic base and placed on the institute's roof located in the immediate vicinity of the Arabian Sea. The exposure time was over 6 months. The samples were taken off from the panel after the completion of the exposure test. The exposed samples were then physically examined, photographed, cleaned, and weighed. Figure 2 shows the photographs of the samples after the exposure. The scribed and uncoated metallic samples show indication of corrosion, whereas coated samples appear to be unaffected by exposure to atmosphere.

3.2.2 Immersion Tests. Two types of immersion tests, namely; immersion in 5% NaCl solution, and exposure to splash zone (in seawater) were carried out. Immersion tests in 5% NaCl were carried out in the laboratory under static conditions. Immersion tests in splash zone were conducted in the Arabian Sea near the intake area of the Al-Jubail plant. For immersion tests in the splash zone, the samples were fixed in a special panel and then caged in a net to prevent being washed away by the waves, especially during high tide or under high wind conditions. The immersion tests were of about 6-month durations. After the immersion tests, the samples were taken out from the panels, visually examined, and photographed. The photographs of the samples after immersion in 5% NaCl and seawater are shown in Fig. 3 and 4, respectively.

3.2.3 Salt Fog Tests. The coated steel and rebar concrete samples (both scribed and unscribed) along with uncoated steel and rebar concrete samples were subjected to salt-spray tests. The samples without the scribe marks were weighed before starting the salt-spray tests. After the required exposure period, the samples were examined as per ASTM D1654-79a (Re-approved 1984). The method provides means of evaluating and comparing basic performance of substrate, pretreated or

Fig. 3 Photograph of the test samples after immersion in 5% NaCl

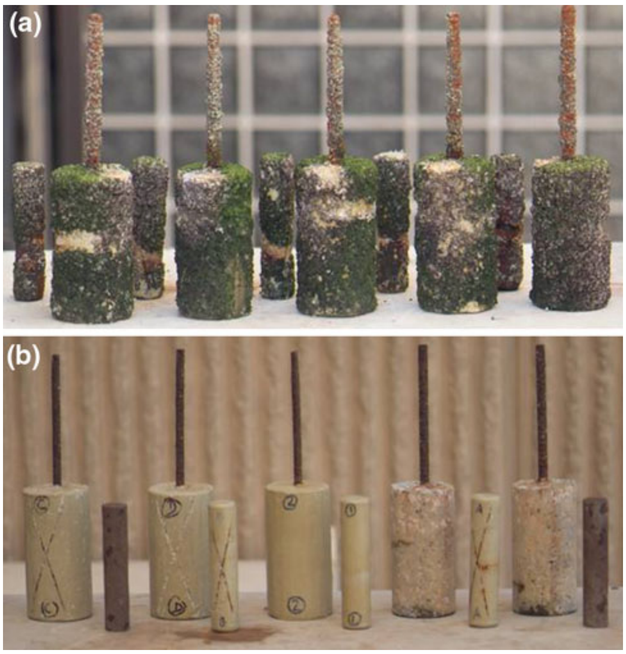


Fig. 4 Photograph of the test samples after immersion in seawater (a) before cleaning and (b) after cleaning

coating system, or composition of coating system, or combinations thereof, after exposure to corrosive environment. After exposure to the required period (1 month), the specimens were carefully removed from the holder and gently washed in water to remove salt deposits from their surface. Figure 5 shows the photograph of the samples after completion of the salt-spray test. Exposed surfaces at the scribes were cleaned with brush to remove all the corrosion products. Mean creepage from the scribed and failed area was measured and rated as per ASTM D1654-79a. The scribed coated metallic and scribed coated rebar concrete samples did not show deep corrosion.

3.2.4 Tests in Sabkha Soil. The Sabkha soil refers to the flat area between a desert and an ocean characterized by a crusty surface consisting of evaporite deposits, windblown sediments, and tidal deposits and is formed primarily through the evaporation of sea water that seeps upward from a shallow water table and through the drying of windblown sea spray. The test samples were buried in sabkha soil area to a depth of about 1 m to test their performance. The exposure time to the soil was about 8 months. After the exposure, the buried samples were taken out and dusted off and followed by physical examination for erosion and corrosion. The photograph of the test specimens in the trench after burying in the sabkha soil is shown in Fig. 6.

Fig. 5 Photograph of the test samples after salt-spray test

Fig. 6 Photograph of the test samples in the trench after burying in the sabkha soil

3.2.5 Electrochemical Polarization Studies. Polarization technique was employed to investigate the corrosion behavior of polyurethane-coated rebar concrete specimens after exposure to different environments. The technique was used for determining corrosion potential, E_{corr}, and corrosion current, I_{corr}, from potentiodynamic polarization plots (potential vs. current plots) in accordance with ASTM G59-78. Uncoated and polyurethane-coated rebar concrete specimens, obtained after corrosion experiments, were used for electrochemical polarization studies. The experiments were performed at ambient temperature (20-30°°C). Electrochemical polarization measurements were carried out on an EG&G model 342-2 soft C_{orr} measurement system. The system consisted of 273 EG&G potentiostat, model 342 C_{orr} software, and 30 IBM PS-2 system. The experiments were carried out with the specimen, contained in a plastic bucket, as a working electrode with the saturated calomel and graphite as reference and counter electrodes, respectively. After stabilization of rest potential (E_{corr}), the scan was taken at the rate of 10 mV/min in the range of −1000 to +1600 mV vs. E_{corr}. For each curve, the corrosion potential, E_{corr}, and corrosion current, I_{corr}, were recorded automatically.

3.2.6 AC Impedance Studies. AC Impedance tests were carried out on uncoated rebar concrete (control), polyurethane-coated concrete and scribed samples exposed to different environments. The main objective of AC Impedance measurements was to evaluate quantitatively the corrosion behavior of polyurethane coating on rebar in concrete exposed to different environments. The measurements were carried out using a Solartron AC Impedance System, which is composed of a 1250 B frequency response analyzer with a blank front panel, and a 1287 electrochemical interface unit. Uncoated rebar concrete, polyurethane-coated rebar concrete, and scribed, coated rebar concrete specimens, obtained after corrosion experiments, were used for AC impedance studies. The experiments were performed at ambient temperatures (20-30 °C).

4. Results and Discussion

4.1 Atmospheric Exposure Tests

Table 1 summarizes the weight changes in coated and uncoated samples, after exposure to atmosphere. The uncoated metallic samples showed a small weight loss of about 4.1 g/kg which corresponds to a corrosion rate of 20 mpy. The coated metallic samples showed no change in weight after 6 months exposure. The coated and uncoated rebar concrete sample showed an identical weight loss of 0.7 g/kg, which is attributed to the exposure of a small portion of rebar. This shows the good resistance offered by polyurethane coating against atmospheric corrosion. However, there is slight discoloration of coating on exposure to atmosphere. The scribed samples also showed superficial corrosion at the scribe, but there is no depth of corrosion.

4.2 Immersion Test

4.2.1 Immersion Tests in 5% NaCl. Table 2 provides weight loss data recorded during immersion in 5% NaCl. The uncoated rebar concrete samples showed a weight gain of about 40 g after exposure of 6 months. The weight gain is due to corrosion of the exposed rebar, when it comes into contact with 5% NaCl solution. The uncoated metallic samples showed weight losses which correspond to corrosion rate of about 100 mpy. The polyurethane-coated steel showed no change in weight after immersion in 5% NaCl, but polyurethane-coated rebar concrete sample showed a slight gain of 1.14 g/kg which is due to exposure of a small portion of rebar. The scribed coated metallic samples show deep penetration of the corrosion product, whereas scribed coated rebar concrete samples do not show any corrosion growth.

4.2.2 Exposure to Splash Zone in Seawater. Table 3 provides weight loss data recorded during exposure to splash zone. Uncoated metallic samples showed heavy corrosion after 6 months exposure in seawater. However, coated samples did not show any weight change indicating excellent protection provided by the polyurethane coating to the steel in seawater. All the samples were found covered with green algae and other biological products during exposure to seawater.

4.2.3 Salt Fog Tests. The uncoated metallic samples showed weight losses of about 11.4 g/kg which correspond to corrosion rate of about 50 mpy. The coated metallic samples showed no weight loss during 1 month test. The uncoated rebar concrete samples showed weight gains of about 20 g/kg, the polyurethane coating drastically reduced the weight loss to 0.8 g/kg. In general, the presence of coating had a very significant effect in reducing corrosion rates of steel as indicated by the experimental data. The scribed samples subjected to salt-spray testing show some corrosion, though the depth of corrosion at the scribes is not deep. The salt-spray test results are summarized in Table 4.

Table 1 Results of atmospheric corrosion tests

S. No.	Description of samples	Initial wt., g	Wt. after cleaning	Remarks
1	Coated metallic	870.0	870.0	No weight loss
2	Coated rebar concrete	1923.3	1922.4	Weight loss: 0.5 g/kg
3	Uncoated rebar concrete	1820.2	1818.9	Weight loss: 0.71 g/kg
4	Uncoated rebar concrete	1809.2	1808.0	Weight loss: 0.66 g/kg
5	Uncoated metallic	819.1	815.7	Weight loss: 4.1 g/kg Corrosion rate: 20 mpy
6	Uncoated metallic	818.5	815.3	Weight loss: 3.9 g/kg Corrosion rate: 20 mpy
A	Scribed coated metallic	…	…	Only superficial corrosion
B	Scribed coated metallic	…	…	Only superficial corrosion
C	Scribed rebar coated concrete	…	…	Only superficial corrosion
D	Scribed rebar coated concrete	…	…	Only superficial corrosion

Table 2 Results of immersion tests in 5% NaCl solution

S. No.	Description of samples	Initial wt., g	Wt. after cleaning	Remarks
1	Coated metallic	866.9	866.9	No weight loss
2	Coated rebar concrete	1836.7	1838.8	Weight gain: 1.14 g/kg
3	Uncoated rebar concrete	1706.4	1746.5	Weight gain: 23 g/kg
4	Uncoated rebar concrete	1723.3	1768.0	Weight gain: 25.9 g/kg
5	Uncoated metallic	815.1	808.8	Weight loss: 7.7 g/kg Corrosion rate: 100 mpy
6	Uncoated metallic	822.1	815.9	Weight loss: 7.5 g/kg Corrosion rate: 100 mpy
A	Scribed coated metallic	…	…	Corrosion
B	Scribed coated metallic	…	…	Corrosion
C	Scribed coated rebar concrete	…	…	No corrosion
D	Scribed coated rebar concrete	…	…	No corrosion

Table 3 Results of immersion test in sea

S. No.	Description of samples	Initial wt., g	Wt. after cleaning	Remarks
1	Coated metallic	865.5	865.2	Weight loss: 0.35 g/kg
2	Coated rebar concrete	1911.4	1905.8	Weight loss: 2.92 g/kg
3	Uncoated rebar concrete	1706.4	…	…
4	Uncoated rebar concrete	1796.7	…	…
5	Uncoated metallic	815.1	761.2	Weight loss: 91.0 g/kg
6	Uncoated metallic	822.1	809.8	Weight loss: 15.0 g/kg
A	Scribed coated metallic	…	…	…
B	Scribed coated metallic	…	…	…
C	Scribed coated rebar concrete	…	…	…
D	Scribed coated rebar concrete	…	…	…

Table 4 Results of salt-spray tests

S. No.	Description of samples	Initial wt., g	Wt. after exposure	Wt. after cleaning	Remarks
1	Coated metallic	855.7	856.0	855.7	No weight loss
2	Coated metallic	866.6	867.0	866.6	No weight loss
3	Coated rebar concrete	1910.7	1914.4	1912.2	Weight loss: 0.78 g/kg
4	Coated rebar concrete	1908.0	1910.4	1908.0	No weight change
5	Uncoated rebar concrete	1788.7	1831.7	1824.0	Weight gain = 19.7 g/kg
6	Uncoated rebar concrete	1790.4	1838.7	1829.7	Weight gain = 21.9 g/kg
7	Uncoated metallic	823.1	828.8	813.7	Weight loss = 11.4 g/kg Corrosion rate: ~75 mpy
8	Uncoated metallic	821.1	826.5	812.5	Weight loss = 10.4 g/kg Corrosion rate: ~75 mpy
A	Scribed coated metallic	…	…	…	No deep corrosion
B	Scribed coated metallic	…	…	…	No deep corrosion
C	Scribed coated rebar concrete	…	…	…	No deep corrosion
D	Scribed coated rebar concrete	…	…	…	No deep corrosion

Table 5 Results of sabkha soil tests

S. No.	Description of samples	Initial wt., g	Wt. after cleaning	Remarks
1	Coated metallic	864.7	864.8	Weight gain: 0.11 g/kg
2	Coated rebar concrete	1898.3	1898.2	Weight loss: 0.05 g/kg
3	Uncoated rebar concrete	1775.7	1828.7	Weight gain: 29.8 g/kg
4	Uncoated rebar concrete	1781.0	1831.3	Weight gain: 28.2 g/kg
5	Uncoated metallic	820.7	820.0	Weight loss: 0.85 g/kg Corrosion rate: 3 mpy
6	Uncoated metallic	821.9	821.5	Weight loss: 0.50 g/kg Corrosion rate: 3 mpy
A	Scribed coated metallic	…	…	No corrosion
B	Scribed coated metallic	…	…	No corrosion
C	Scribed coated rebar concrete	…	…	No corrosion
D	Scribed coated rebar concrete	…	…	No corrosion

4.2.4 Tests in Sabkha Soil. The 8-month-long sabkha soil burial test of uncoated metallic samples showed weight losses of 0.5-0.8 g/kg which corresponds to a corrosion rate of about 3 mpy compared to polyurethane coated metallic samples with virtually very little (<0.1 g) or no weight loss. The coated concrete samples show negligible weight losses of 0.05 g/kg. The scribed samples do not show any evidence of corrosion, the scribes appear to be free from corrosion products. In general, coating show quite good resistance to sabkha soil. The sabkha soil burial results are summarized in Table 5.

4.2.5 Electrochemical Polarization Studies. Potentiodynamic polarization curves representing rebar concrete uncoated (control), coated and coated scribed samples exposed to different corrosive environments are shown in Figure 7-9, and the electrochemical parameters as determined from potentiodynamic studies are listed in Table 6. For immersion in 5% NaCl solution for 6 months (Fig. 7), the coated rebar concrete samples showed a decrease in corrosion current, I_{corr}, from 0.684 to 0.00012 μA/cm^2, and a shift in corrosion potential, E_{corr}, from -682 to -150 mV. The scribed sample shows

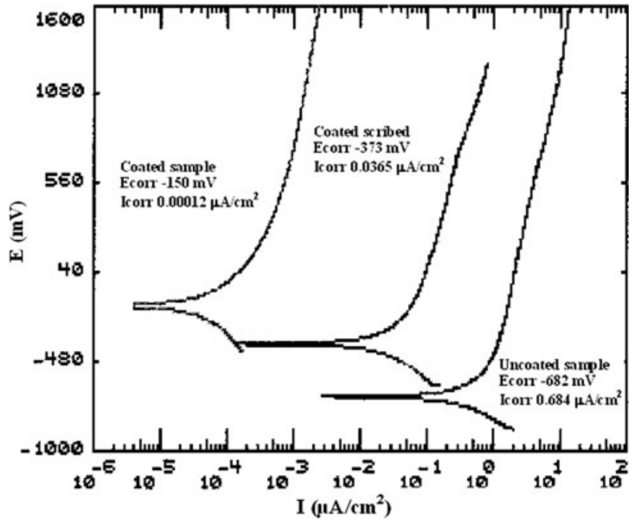


Fig. 7 Potentiodynamic polarization curves for uncoated, coated, and coated scribed rebar concrete samples immersed for 6 months in 5% NaCl solution

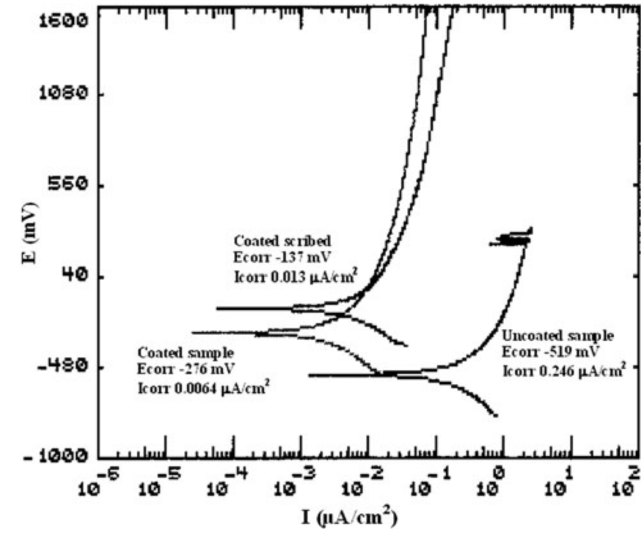


Fig. 9 Potentiodynamic polarization curves for uncoated, coated, and coated scribed rebar concrete samples buried for 8 months in sabkha soil

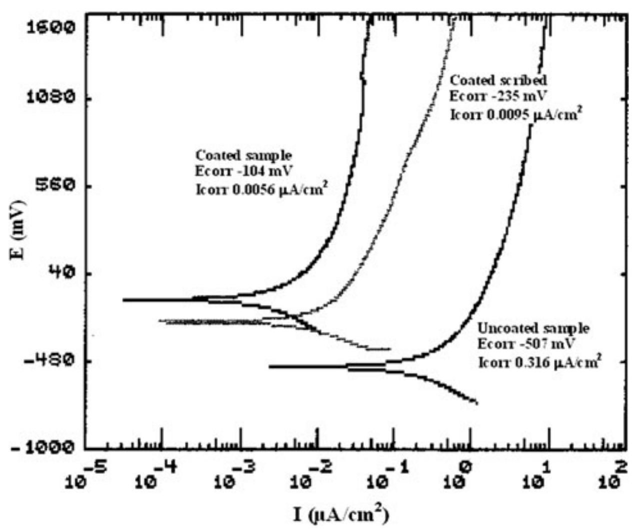


Fig. 8 Potentiodynamic polarization curves for uncoated, coated, and coated scribed rebar concrete samples immersed for 6 months in splash zone of seawater

lowering of I_{corr} (0.0365 μA/cm^2) and increase in E_{corr} (−373 mV). The negative shift in I_{corr} and a positive shift in E_{corr} signify the protections provided by the polyurethane coating. The results for the samples exposed to splash zone for 6 months (Fig. 8) indicated a decrease in I_{corr} from 0.316 to 0.0056 μA/cm^2 and a shift in E_{corr} from −507 to −104 mV. The corresponding values for scribed samples are 0.0095 μA/cm^2 and −235 mV. These results show reduction in corrosion in the presence of Souplethane coating. For immersion in splash zone (Fig. 9), similar trends as those observed in case of 5% NaCl and splash zone environment are observed. The polyurethane coating shows good barrier properties.

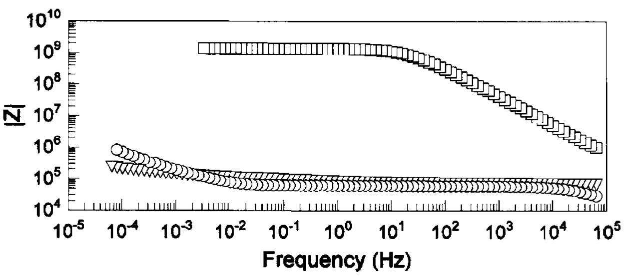
4.2.6 AC Impedance Studies. Bode curves were obtained by plotting real impedance |Z| vs. frequency and theta (θ) vs. frequency to study the corrosion behavior of uncoated and coated materials in different environments. The magnitude of impedance and change in impedance with increasing frequency provides information regarding the corrosion behavior of materials. The typical Bode plots are shown in Fig. 10-14. The results of AC impedance studies are summarized in Table 7. The Bode plots [real impedance |Z| vs. |frequency|] of the coated materials provided useful information regarding the corrosion behavior of materials. The initial impedance of the coating and its rate of change (reduction) are the important parameters in the evaluation of coatings and predicting its future performance. A coating is rated as excellent if the initial electrochemical impedance is $>10^9$ ohm-cm^2, good if it is in the range of 10^8-10^9, and fair if the value is in the range of 10^7-10^8 ohm-cm^2 (Ref 8). The coating is rated as poor if the initial electrochemical impedance is $<10^7$ ohm-cm^2. The values of electrochemical impedance for the polyurethane coated rebar concrete samples after exposure to different corrosive environments were in the range of 4.3×10^7 to 6.5×10^{11} ohm-cm^2 indicating that the performance of coating was fair to excellent. It may be noted that the above values are obtained after 6-8 months' exposure to the corrosive environment. Bode plots for polyurethane-coated rebar samples showed the highest impedance in salt fog (least aggressive) and the lowest impedance in sabkha (most aggressive).

4.2.7 Condition of the Rebar in Exposed Specimens. The conditions of the rebar in uncoated and coated concrete specimens after exposure to different environments were assessed by breaking of the exposed specimens and subsequently examining them visually. The rebar of the polyurethane-coated and scribed samples did not show any sign of corrosion; only the rebar in uncoated samples were found corroded. These observations indicate the good barrier properties of polyurethane coating in different environments.

4.2.8 Adhesion Properties of the Coating. When the coated samples were broken under a compressive load, the coating appeared to be detached either partially or wholly from the substrate. Figure 15 and 16 show typical photographs showing detachment of the coating from the concrete and steel substrate. The coating is totally detached from the rebar concrete structure. After exposure, the scribed coated sample

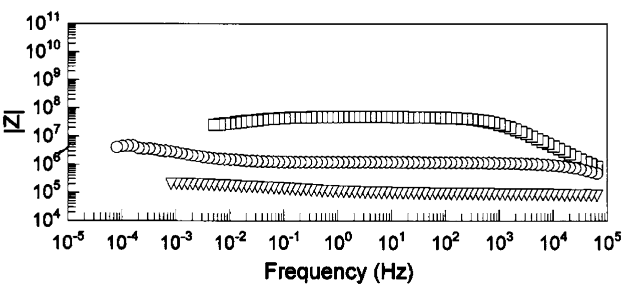
Table 6 Electrochemical parameters as determined from potentiodynamic studies

S. No.	Sample	Environment	Exposure time, months	E_{corr}, mV	I_{corr}, μA/cm^2
1.	Uncoated rebar concrete (control)	5% NaCl	6	−682	0.684
2.	Coated rebar concrete	5% NaCl	6	−150	0.00012
3.	Coated rebar concrete scribed	5% NaCl	6	−373	0.0365
4.	Uncoated rebar concrete (control)	Splash zone	6	−507	0.316
5.	Coated rebar concrete	Splash zone	6	−104	0.0056
6.	Coated rebar concrete scribed	Splash zone	6	−235	0.0095
7.	Uncoated rebar concrete (control)	Sabkha	8	−519	0.246
8.	Coated rebar concrete	Sabkha	8	−276	0.0064
9.	Coated rebar concrete scribed	Sabkha	8	−137	0.013



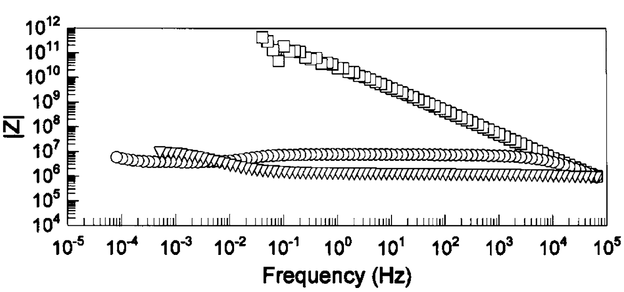
□ - Coated, O- Coated scribed, Δ – Uncoated

Fig. 10 Bode plots for test samples immersed in 5% NaCl solution for 6 months



□ - Coated, O- Coated scribed, Δ – Uncoated

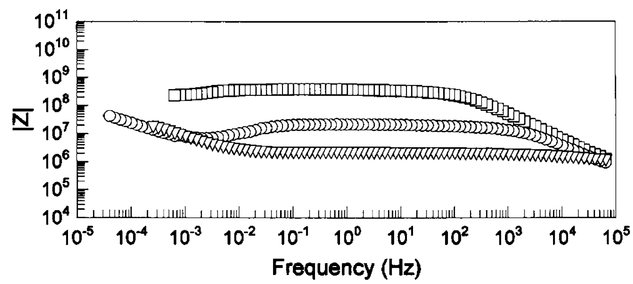
Fig. 11 Bode plots for test samples buried in sabkha soil for 8 months



□ - Coated, O- Coated scribed, Δ – Uncoated

Fig. 12 Bode plots for test samples exposed to salt fog for 1 month

appeared to be corroded. The coating could be peeled off easily showing an adhesion failure. Adhesion failure (peeling, flaking, delamination, etc.) occurs when, in the presence of opposing



□ - Coated, O- Coated scribed, Δ – Uncoated

Fig. 13 Bode plots for test samples exposed to atmosphere for 6 months

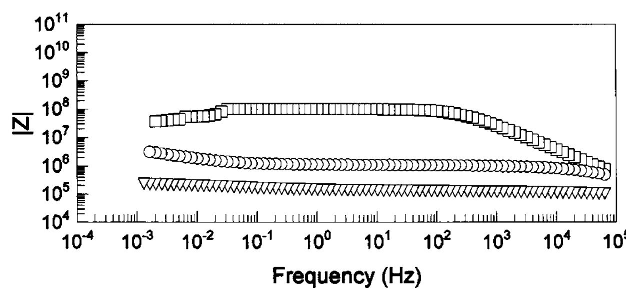


Fig. 14 Bode plots for test samples exposed to seawater splash zone for 6 months

stresses, the adhesive forces are insufficient to hold the coating to be substrate. In spite of good corrosion resistance properties, the polyurethane coating has poor adherence.

5. Conclusions

1. The coating on steel and rebar concrete showed good resistance to atmospheric exposure, immersion in 5% NaCl, sabkha soil burial, salt fog test, and excellent protection toward splash zone. However, there was some discoloration of the coating during exposure to atmosphere.
2. Potentiodynamic polarization studies carried out on the coated rebar concrete samples exposed to 5% NaCl, splash zone, and sabkha soil showed a significant lowering in corrosion current, I_{corr}, and increase in corrosion potential, E_{corr} values, as compared with the uncoated rebar in the concrete.

Table 7 Results of AC impedance studies

S. No.	Sample	Environment	Exp time, months	Rp, Ω
1.	Uncoated rebar concrete	5% NaCl	6	1.0×10^5
2.	Uncoated rebar concrete	Splash zone	6	6.2×10^4
3.	Uncoated rebar concrete	Atmosphere	6	1.1×10^7
4.	Uncoated rebar concrete	Salt fog	1	6.4×10^6
5.	Uncoated rebar concrete	Sabkha	8	7.5×10^4
6.	Coated rebar concrete	5% NaCl	6	1.1×10^9
7.	Coated rebar concrete	Splash zone	6	9.1×10^7
8.	Coated rebar concrete	Atmosphere	6	2.9×10^8
9.	Coated rebar concrete	Salt fog	1	6.5×10^{11}
10.	Coated rebar concrete	Sabkha	8	4.3×10^7
11	Scribed coated rebar concrete	5% NaCl	6	5.5×10^5
12	Scribed coated rebar concrete	Splash zone	6	2.2×10^6
13	Scribed coated rebar concrete	Atmosphere	6	1.3×10^7
14	Scribed coated rebar concrete	Salt fog	1	6.6×10^7
15	Scribed coated rebar concrete	Sabkha	8	2.7×10^6

Fig. 15 Photograph showing detachment of the coating from the concrete substrate

3. The AC impedance results showed that the performance of coating in different corrosive environments varied from fair to excellent.
4. For the coated samples, when broken under a compressive load, the coating appeared to be detached either partially or wholly from the substrate.

6. Recommendations

1. In general, the polyurethane has been found to possess good resistance to seawater, marine atmosphere, and sabkha soil and may be applied on structural components exposed to marine environment.
2. The coating appeared to detach from the substrate under applied stress. This significant drawback makes polyurethane coating unqualified for applications in pipes and tanks subjected to turbulent flow, and other structural components which are exposed to product water, seawater, soil, and atmosphere, and prone to scribal or notching phenomenon.

Fig. 16 Photograph showing detachment of the coating from the steel substrate

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