JMEPEG (2010) 19:984–994
DOI: 10.1007/s11665-009-9565-9

1059-9495/$19.00

Corrosion of Bare and Galvanized Mild Steel in Arabian Gulf Environment

H. Saricimen, A. Ahmad, A. Quddus, A. Aksakal, A. Ul-Hamid, and T.A. Siddique

(Submitted January 4, 2009; in revised form September 22, 2009)

Corrosion performance of bare and galvanized mild steel in atmospheric, soil and splash zone exposure conditions was evaluated at a Khaleej Mardumah test station (KMTS) in Jubail Industrial City (JIC) located at Arabian Gulf coast. The samples were exposed for a period of 15 months. During the exposure, the environmental conditions were periodically monitored by analysis of air, soil, groundwater, and sea-water samples. The corroded mild steel and galvanized steel samples were examined by SEM, XRD and XRF to identify the corrosion products and study their surface morphology. Weight loss method was employed to determine the corrosion rates. The experimental results showed that intense temperature and humidity variations as well as high chloride and sulfate concentrations in the region result in severe corrosion of bare mild steel especially under the splash zone conditions. A comparison with the corrosion data for other parts of the world shows that atmospheric and soil environments at the selected test site are significantly corrosive to mild steel. The splash zone, on the other hand, is much more corrosive to mild and galvanized steel than the other parts of the world.

Keywords atmospheric corrosion, galvanized steel, mild steel, rebar, soil, splash zone

1. Introduction

The climatic conditions of the Arabian Gulf are characterized by high-temperature-humidity regimes. The temperature usually rises above 50 °C during summer while dust storms are frequented both in the hot and cold season. The industrial city of Jubail located at the east coast of Saudi Arabia experiences a relative humidity of above 50% during most part of the year. In addition, the atmosphere is laden with pollutants from oil and petrochemical industry located nearby along with high chloride levels due to the city's coastal setting. Daily fluctuations in the temperature can be as much as 20 °C during summer, while the relative humidity can change from 40 to 100% within 24 h. Gulf water has a high rate of sea-salt and the atmosphere has a high content of chloride and sulfate (Ref 1). In addition, sulfur dioxide and organic carbonaceous deposits from burning fuel render the atmosphere in the Gulf region severely corrosive.

Previous investigations have also shown that the soil in Jubail Industrial City (JIC) is also highly corrosive (Ref 2-4) due to the characteristics of the soil, low groundwater level and high salt concentration of ground water. This combination of industrial and coastal environment gives rise to severe exposure conditions that has detrimental effects on structural and construction materials. It is an established fact that the corrosion rate in industrial and marine areas may be several times that in rural region (Ref 5). Also, the corrosion rate in an industrial area may be hundred times greater than that in a desert or arctic region (Ref 5).

Atmospheric corrosion results from the conjoined action of oxygen and moisture. The corrosion reaction takes place in the cells of anodes and cathodes that operate in the presence of a limited amount of neutral or slightly acidic electrolyte. Atmospheric corrosion results in more failures on a cost and tonnage basis than corrosion in any other environment (Ref 5). The extent of corrosion depends on "time of wetness" which is controlled by atmospheric parameters such as humidity, pollutants, rainfall and temperature. For instance, the atmospheric corrosion rate of metals rises sharply when the relative humidity increases above a level termed *critical relative humidity* (Ref 6-8). This level occurs between 50 and 70% for common engineering materials such as steel, nickel, copper and zinc.

Underground metallic corrosion in soil is a physical and biochemical process, which results in electron loss and dissolution of metal from the metal surface. The soil contains salts, acids, alkalis and organic compounds and the interaction of factors such as soil moisture, the conductivity of the solution, pH, the oxygen concentration (aeration) and bacteria that affect oxidation-reduction reactions also influences the corrosion process (Ref 9-11). Generally, it can be stated that soils of low resistivity containing significant concentrations of chloride and sulfate ions are usually more corrosive. The presence of sulfides and sulfates is often an indicator of sulfate reducing bacteria (SRB). These bacteria can shift the pH in the acidic direction, causing an increase in corrosion. The higher the content of calcium carbonate in the soil, the lower becomes the corrosion rate.

Engineering components located in the vicinity of seawater but not immersed in it can also get corroded severely due to

H. Saricimen, A. Ahmad, A. Quddus, A. Ul-Hamid, and **T.A. Siddique**, Research Institute, Center for Engineering Research, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia; and **A. Aksakal**, Royal Commission for Jubail and Yanbu, Jubail Industrial City, Eastern Province, Saudi Arabia. Contact e-mail: sarici@kfupm.edu.sa.

being in the splash zone or half-immersion zone. The surfaces of these components will go through wet and dry cycles. Dissolved oxygen is more readily transported through a thin layer of surface water as experienced under splash zone conditions than through bulk water during complete immersion. Thus, corrosion in the splash zone is higher than in full immersion (Ref 5).

This study investigates the corrosivity of environment and the long-term corrosion performance of bare mild steel (in the form of coupons and rebars) and galvanized mild steel (coupons) materials in atmosphere, soil and splash zone conditions.

2. Experimental Procedure

2.1 Material Composition

The chemical composition of bare and galvanized mild steel samples used in this study is given in Table 1.

2.2 Preparation of Exposure Racks and Samples

Exposure frames, racks and coupons were prepared by following ASTM standards G50 (Ref 12), G1 (Ref 13) and G46 (Ref 14). The frames and racks were fabricated from 2-in. SS304 angles. The corrosion coupons were mounted on the frames using stainless steel bolts and nuts along with Teflon washers. Corrosion coupons of mild steel were machined in quadruplet to 10×15 cm size from 3-mm-thick sheet. The coupons were trimmed around the edges for a smooth surface. A hole of 5 mm diameter was machined at the center of all the coupons to tie the identification (ID) number tags with a self-locking plastic string. The numbers were also engraved on the top left corner on one side of all the coupons. The coupons were cleaned with gasoline and acetone, then wiped dry and weighed. The results were recorded as initial weight of coupons before exposure to the environment, ASTM G1 (Ref 13). One set of mild steel samples was used in the form of rebars which were machined to 15 cm length from 16 mm diameter deformed product. They were fixed to special holders on the frames with self-locking plastic strings. Another set of mild steel coupons was galvanized with a 25 μm layer of Zn using electroplating.

Corrosion samples for all three sets of samples, i.e. mild steel coupons, mild steel rebars and galvanized mild steel coupons, were exposed to atmospheric, soil and splash zone conditions for 15 months. The atmospheric and splash zone coupons were fixed on stainless steel frames and installed on stainless steel racks facing southward direction at 30° angle with the horizontal, at 80 cm height from the ground at the lowest edge. The underground coupons were buried in perforated plastic containers at 70 cm depth from the ground surface.

Table 1 Chemical composition of bare and galvanized mild steel coupons and rebar used in this study

	Chemical composition, wt.%							
Material	**Fe**	**C**	**Cr**	**Cu**	**Mn**	**Al**	**Ni**	**Si**
Bare mild steel coupon	98.7	0.16	0.03	0.07	1.06	0.09	…	…
Bare mild steel rebar	98.89	0.09	0.09	…	0.68	…	0.05	0.20
Galvanized mild steel coupon	Mild steel coupons coated with 25 μm thick layer of Zn layer using electroplating							

Table 2 Air concentrations of total suspended particulate matter (TSP), chloride, and sulfate at the test site

	Concentration, μg/m^3				
Month of sampling	**TSP (a)**	**Chloride (a)**	**Sulfate (a)**	**Max RH, %**	**Monthly rain, mm**
December 2004	70.39	1.03	13.93	100	78.0
January 2005	224.31	3.60	27.26	100	21.0
February 2005	39.88	3.62	12.41	100	5.0
March 2005	48.24	5.81	12.44	100	4.8
April 2005	228.43	8.94	49.65	100	0.0
May 2005	301.99	5.95	16.16	93	0.0
June 2005	191.19	4.47	12.41	71	0.0
July 2005	366.89	6.12	20.65	98	0.0
August 2005	439.59	6.28	15.91	97	0.0
September 2005	117.26	<0.1	22.86	96	0.0
October 2005	641.16	1.68	18.31	96	0.0
November 2005	156.44	6.45	16.65	98	2.4
December 2005	107.42	3.68	15.55	100	0.0
January 2006	30.91	6.18	9.15	100	0.4
February 2006	151.98	4.36	25.32	100	7.0

(a) TSP, chloride, and sulfate samples were collected for only 24 h during the month

2.3 Corrosivity of Environment

Corrosivity of the environment was monitored periodically by retrieving samples from the soil, groundwater, seawater, and atmosphere at the test site and analyzing them in the laboratory. Air samples were analyzed for the total suspended particulate (TSP) matters, chloride, sulfate and trace metals. Soil samples were analyzed for chloride and sulfate contents. Seawater and groundwater samples were tested in situ for dissolved oxygen, conductivity, odor, color, and temperature. Samples of the same were also analyzed in the laboratory for corrosive agents such as chloride, sulfate, oxygen, and carbonate. The samples were analyzed for anions by ion chromatography. On-site measurements, namely (i) groundwater table movement, (ii) tidal elevation, (iii) soil temperature, (iv) groundwater temperature, and (v) seawater temperature, were performed using a range of sensors, gauges, and data-loggers. Hourly meteorological data consisting of air temperature (T), relative humidity (RH), wind speed, wind direction, rainfall, and global soil radiation to depict the monthly statistics of minimum, maximum, and average values were also acquired from a local environmental monitoring agency.

2.4 Weight Loss Determination

The samples were cleaned using chemical solutions and mechanical scrubbing and weight loss was determined as recommended in ASTM G-1-90 (Ref 13, 15). A 50-400 g/L (5-40%) solution of concentrated HCl at room temperature was used as the cleaning solution. For galvanized steel coupons, 10% dilute HCl solution at room temperature was used for cleaning. The dried samples were weighed. After the 4th cleaning-weighing cycle, the samples were placed in polyethylene bags and kept for further analyses. The corrosion rate was calculated using the following formula (Ref 15):

$$\mathrm{CR}\ (\mu\mathrm{m/year}) = K \times [\Delta W/(A \times D \times T)]$$

where CR is the corrosion rate (μm/year), K = 87,600, A the area (cm^2), ΔW the weight loss (mg), T the time (h), and D is the density (g/cm^3).

2.5 Laboratory Analysis

The samples were photographed and analyzed for chemical composition using inductively coupled plasma-atomic emission spectrometer (ICP-AES). The corrosion products were analyzed by x-ray fluorescence (XRF) and x-ray diffraction (XRD) methods. Scanning electron microscopy (SEM) coupled with energy dispersive x-ray spectroscopy (EDS) was used to examine the surface morphology of the corrosion products and determine their chemical composition.

3. Results and Discussion

3.1 Atmospheric Analysis

Analysis results of atmospheric samples for chloride, sulfate, TSP matters, maximum relative humidity (RH), and rainfall over a period of 15 months are shown in Table 2. According to the results, the TSP concentration varied between 30.91 and 641.16 $\mu g/m^3$ during the monitoring period. High

Table 3 Results of chemical analysis of soil samples

	Soil analysis mg/L, ppm
Turbidity (NTU)	NA
Carbonate	ND
Sulfate	1410
Chloride	8040

NA, not applicable; ND, not detected

Table 4 Quality characterization (in ppm or mg/L) of groundwater samples

	Month				
Elements	**June**	**October**	**January**	**April**	**October**
pH	7.50	7.26	7.39	7.37	6.72
Temperature, °C	37.0	35.0	17.5	28.0	33.0
Dissolved oxygen	0.3	0.0	7.0	0.0	0.6
Conductivity, μS/cm (a)	73,300	96,000	78,358	83,280	99,701
Turbidity (NTU)	6.90	10.60	2.17	1.9	2.6
Carbon dioxide	1330.0	…	576.0	920.4	372.6
Chloride	34,500	34,211	25,200	29,200	29,900
Sulfate	5410	4886	4940	6860	4840
Calcium	803	350	835	747	757
Magnesium	2380	1020	2100	1890	2160
Potassium	813	356	823	700	736
Silicon	13.80	13.80	6.71		12.1
Sodium	19,900	9250	17,800	15,800	19,800
Strontium	17.60	…	18.3	16.7	18.3
Sulfur	1630	697	1820	1520	1520
TSS	1590	1512	32	50	34
TDS	67,800	64,400	52,500	55,800	66,800

(a) Conductivity is measured as: conductivity (μS/cm) = TDS (mg/L)/0.67

Table 5 Quality characterization (in ppm or mg/L) of seawater samples

	Month				
Elements	**June**	**October**	**January**	**April**	**October**
pH	7.50	7.80	7.12	7.66	7.27
Temperature, °C	37.2	34.5	16.0	25.0	30.0
Dissolved oxygen	4.0	6.1	9.0	3.1	4.7
Conductivity, μS/cm	67,300	95,800	79,403	78,209	92,388
Turbidity (NTU)	0.55	1.01	0.32	0.21	0.7
Carbon dioxide	219	…	76	225.9	143.3
Chloride	29,500	33,616	26,400	27,900	29,100
Sulfate	4240	4791	4180	5770	4500
Calcium	668	314	792	601	639
Magnesium	2110	1050	2290	1810	1910
Potassium	700	327	756	624	678
Silicon	1.17	1.17	2.20	…	2.63
Sodium	17,400	8970	18,500	14,800	18,100
Strontium	11.20	…	14.50	11.20	10.8
Sulfur	1430	678	1660	1350	1390
TSS	1290	1588	212	2	4
TDS	56,000	64,240	53,200	52,400	61,900

concentration of TSP occurred during hot and windy atmospheric conditions. The highest chloride and sulfate concentrations were 8.94 and 49.65 μg/m^3, respectively. The max RH varied between 71 and 100% during the exposure period. The rainfall was concentrated in few months of the years and ranged between 0.0 and 78.0 mm.

Table 6 Chemical composition of corrosion products formed on mild steel and galvanized steel coupons measured using XRF

	Chemical composition of corrosion products, wt.%								
	Corrosion product on MS coupon			Corrosion product on MS rebar			Corrosion product on GS coupon		
Elements	Atmosphere	Soil	Splash	Atmosphere	Soil	Splash	Atmosphere	Soil	Splash
Fe	90.77	67.54	96.45	95.83	70.84	97.20	4.40	0.43	96.93
Mn	1.24	1.53	1.53	1.33	0.68	1.30	0.13	…	1.08
Si	6.2	8.5	…	0.37	13.16	0.3	1.38	…	…
Ca	3.9	17.87	1.71	1.54	12.48	1.61	8.88	3.41	2.27
K	…	1.74	…	1.15	1.79	…	0.88	…	…
Zn	…	…	…	…	…	…	83.22	95.08	0.35
Minor elements	S	1.15S	0.3S	S	…	…	0.72S	0.9S, 0.11Cu	

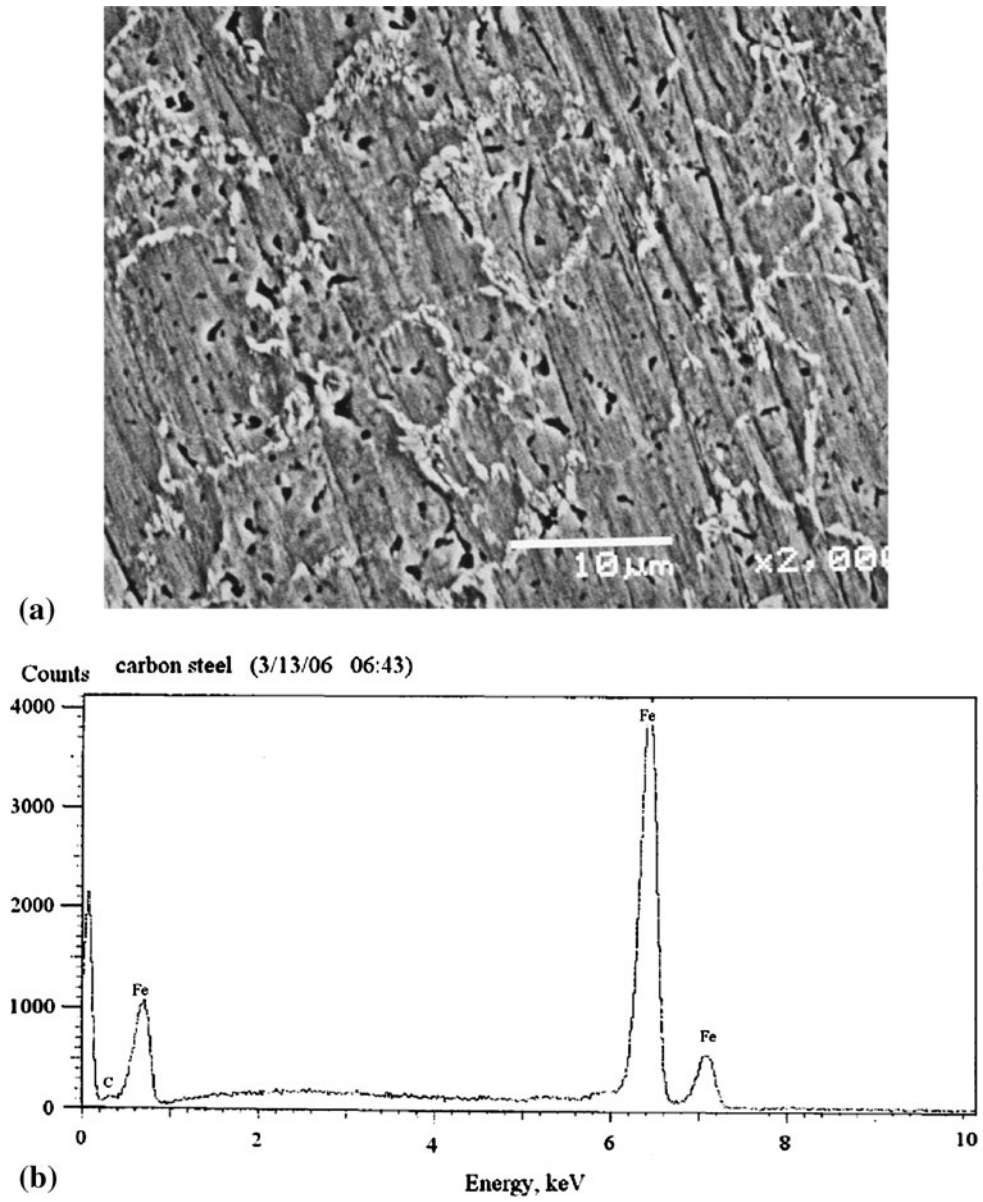

Fig. 1 (a) SEM micrograph of unexposed mild steel coupon along with (b) EDS spectrum obtained from its surface

3.2 Soil, Groundwater, and Seawater Analysis

Concentrations of chlorides and sulfates in the soil samples are shown in Table 3. The results of chemical analysis of ground- and seawater samples are given in Table 4 and 5.

The chloride and sulfate concentrations in the soil were 8040 and 1410 ppm, respectively. The pH values of the ground- and seawater varied between a narrow range of 7 and 8 indicating neutral conditions. The temperature pattern was found to be consistent with the seasonal weather change. Dissolved oxygen (DO) level indicates the level of pollution. The highest DO concentrations occurred during the month of lowest temperature. The concentration of CO_2 was inversely proportional to the DO level. The deterioration in water quality was observed during summer, resulting in a bad odor which develops when sulfate species are reduced to sulfides or H_2S. The conductivity, total dissolved solids (TDS), and salinity levels were comparable for groundwater and seawater where sodium chloride (NaCl) was the major constituent. Regarding soil resistivity, a study conducted earlier in the JIC (Ref 3, 4) showed that generally the resistivity of soil varied between 12 and 4.6×10^6 Ω-cm with an average of 8400 Ω-cm up to 1.5 depth as measured by 4-point Wenner method. Between 1.5 to 3.0 m depth, the resistivity varied between 4 and 9.8×10^6 Ω-cm with an average of 2100 Ω-cm. According to the soil box measurements results obtained in the laboratory, the average soil resistivity varied between 28,000 and 540 Ω-cm as dry and water saturated, respectively.

The present results are consistent with the earlier research results (Ref 4) conducted at three different sites in JIC. The characteristics of soil in Khaleej Mardumah Test Station (KMTS) indicate that soil in this site is more corrosive than the soils in JIC. Total salt content in KMTS soil is 9450 mg/L (Table 3), whereas that in the three JIC sites vary between 2762 and 3593 mg/L (Ref 4). The CR of soils in the three JIC sites also follows a similar trend as the total salt content. The coupons corroded at higher rate in KMTS in a shorter exposure period.

3.3 Visual Observation

The surfaces of mild steel coupon and rebar exposed to atmosphere were covered with dark brown rust which was moderately to strongly adherent; not easily removed by metal spatula. Pitting was observed on the surface of mild steel coupons. The surface of galvanized steel was silvery with only scattered patches of light yellowish brown rust.

Mild steel coupons and rebars exposed to soil were heavily corroded particularly on the lower half surfaces inside the soil. More than 50% of the surfaces were covered with heavy brown rust mixed with sand. The coupons also showed pitting.

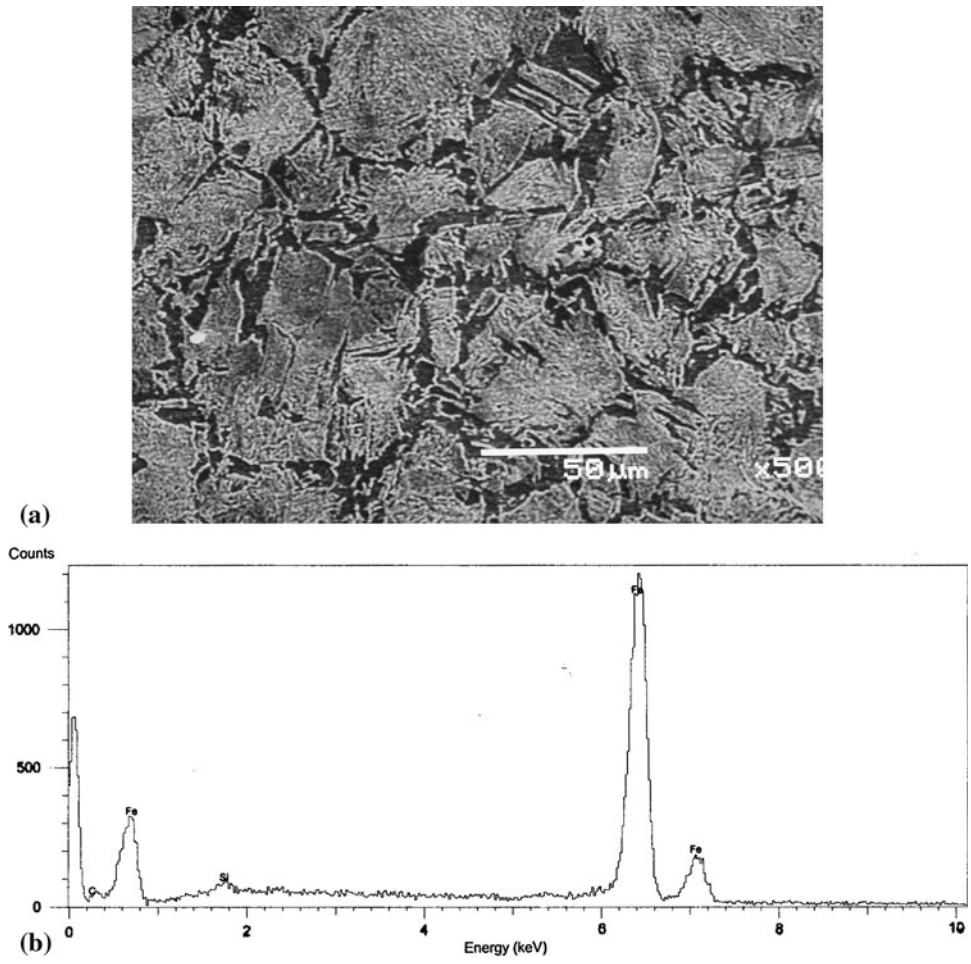

Fig. 2 (a) SEM micrograph of unexposed mild steel rebar along with (b) EDS spectrum obtained from its surface

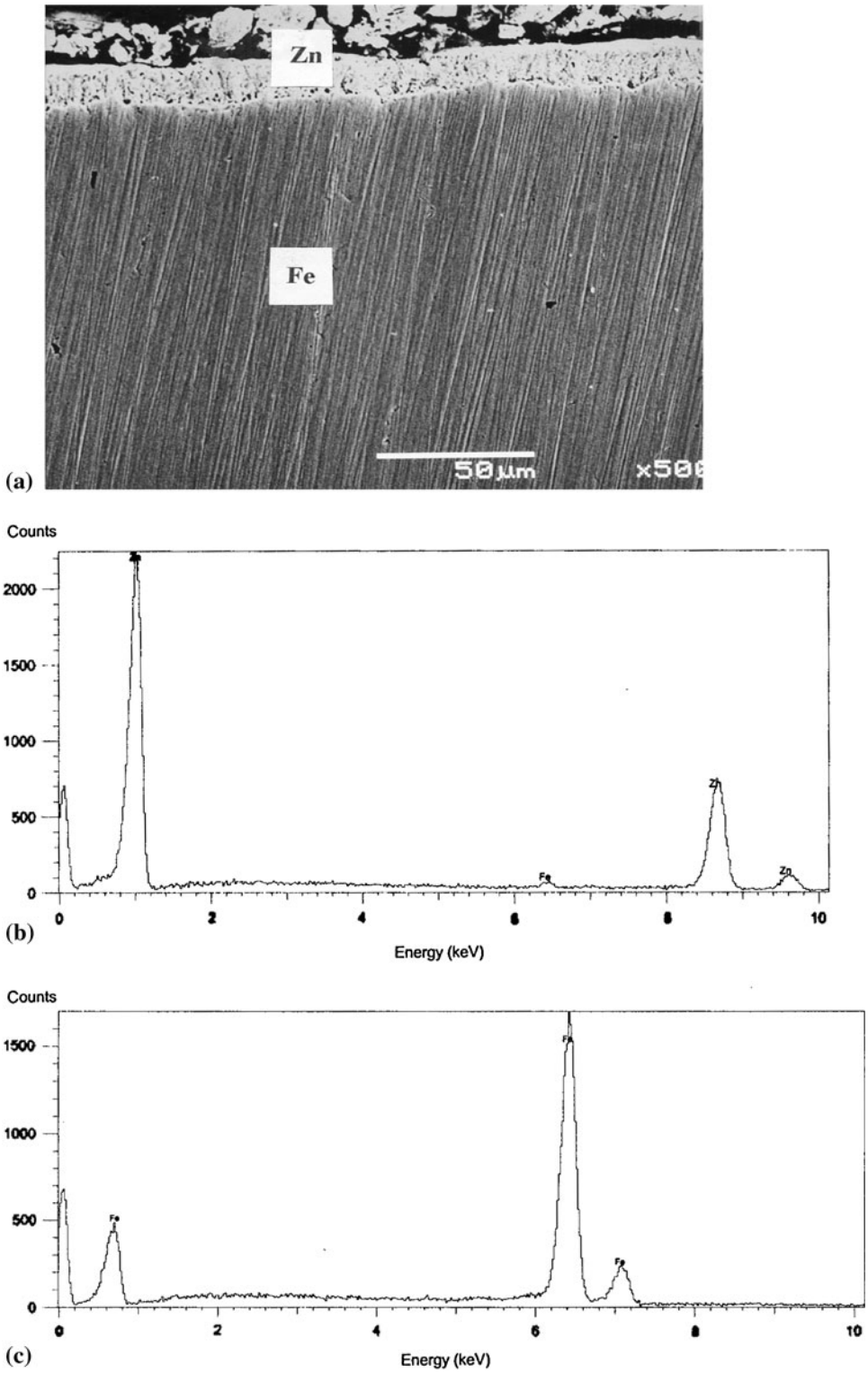

Fig. 3 (a) SEM micrograph of unexposed galvanized mild steel coupon along with EDS spectrum obtained from (b) Zn coating and (c) steel surface

Galvanized steel coupons were covered with well adherent *white rust* on more than 50% of the surfaces. Remaining surface exhibited dark-green to black discoloration.

After splash zone exposure, the bare mild steel coupons were fully covered with non-adherent light to dark brown rust. The rust formed on rebars was adherent and did not cover the whole surface. Galvanized steel formed heavy and loose dark brown corrosion product on most part of the surfaces. Pit formation was also observed.

3.4 XRF and XRD Analyses of Corrosion Products

Corrosion products were scraped into fine powder for analysis by XRF and XRD to determine their elemental

composition and identify constituent phases. The phases were identified automatically by the XRD software in the machine. The "d-spacings" of each and every peak found in a XRD spectrum was matched with the PDF database available in the software program. Table 6 shows the results of XRF analyses for bare and galvanized mild steel coupons/rebars exposed under different environmental conditions. Contaminants like calcium, potassium, and some silicon from the environment were detected.

The corrosion products formed on bare mild steel coupons identified using XRD are as follows:

Atmosphere	Soil	Splash zone
Fe_3O_4 (magnetite) $CaSO_4 \cdot 2H_2O$ (gypsum) MnO_2, SiO_2, $CaCO_3$	FeO(OH) (oxyhydroxide) SiO_2 (quartz) $CaCO_3$	Fe_2O_3 MnO(OH)

The corrosion products formed on rebars are as follows:

Atmosphere	Soil	Splash zone
FeO(OH) (oxyhydroxide) $CaSO_4$ ($2H_2O$)	Fe_2O_3 (H_2O) SiO_2 $CaSiO_3$	FeO(OH) (oxyhydroxide) Fe_3O_4

The corrosion products formed on galvanized mild steel coupons are as follows:

Atmosphere	Soil	Splash zone
$Zn_5(OH)_8Cl_2 \cdot H_2O$ $Zn(OH)_2$ $FeSO_4(OH) \cdot 3H_2O$ $CaCO_3$	$Zn_{12}(OH)_{15}Cl_3(SO_4)_3 \cdot 5H_2O$ $Zn_5(OH)_8Cl_2 \cdot H_2O$ $CaCO_3$	$Fe_2O_3 \cdot H_2O$ Fe_3O_4

Mild steel corroded in the presence of moisture, chloride, and sulfate ions in the atmosphere. Any iron chlorides or iron sulfates that may have been produced during the corrosion reactions are eventually converted into iron oxides as indicated by the presence of magnetite and iron oxyhydroxide. Due to a washing effect in the splash zone, calcium in the corrosion products was insignificant and calcite peaks were not observed in XRD spectra.

Zinc corroded and protected the substrate steel from corrosion, thereby constituting a large proportion of the corrosion products formed under exposure in atmosphere and soil environment. However, Zn coating was severely damaged during exposure in the splash zone, resulting in the corrosion of underlying steel as demonstrated by the presence of Fe-oxides.

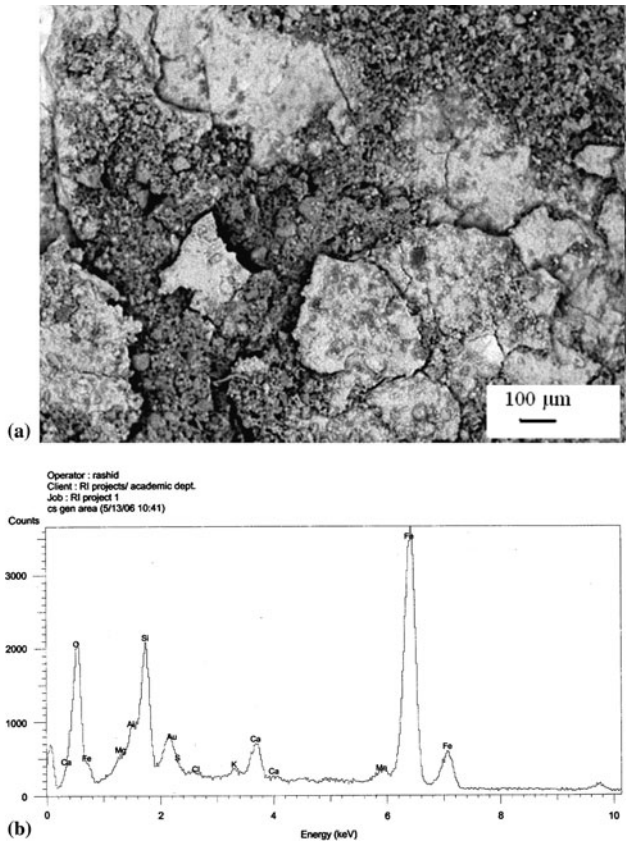

Fig. 4 (a) SEM micrograph of corroded mild steel coupon surface exposed to the atmosphere for 15 months. (b) EDS spectrum obtained from the same region showing the presence of Fe, O, Si, Ca, Al, K, and Mg

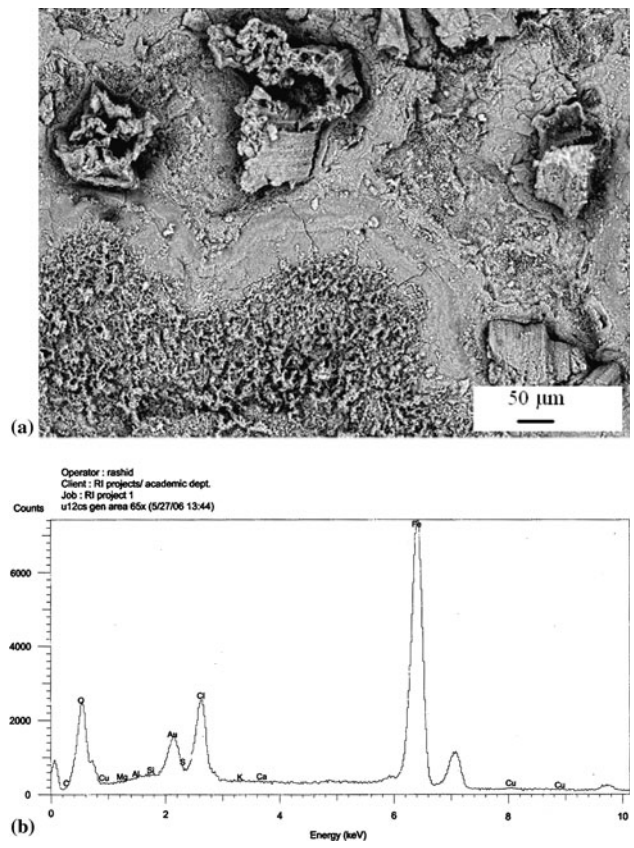

Fig. 5 (a) SEM micrograph of mild steel coupon exposed to soil environment showing the formation of a corrosion product. (b) EDS spectrum obtained from the same region showing the presence of Fe, O, and Cl

3.5 SEM/EDS Analysis

The etched microstructures of the unexposed control samples of bare mild steel coupon and rebar along with their EDS spectra are shown in the SEM micrographs of Fig. 1(a) and (b) and 2(a) and (b), respectively. The samples had similar microstructures showing regions of pearlite and ferrite. Figure 3(a) shows a cross-sectional view of unexposed Zn coated steel along with the EDS spectra obtained from the coating as well as the steel substrate. The coating (20-25 μm in thickness) appeared to be intact and adherent to the underlying mild steel substrate.

Figure 4(a) shows the surface morphology of the corrosion product formed on bare mild steel coupon exposed to the atmosphere for 15 months. The surface is uniformly covered with a corrosion product. The EDS spectrum (Fig. 4b) shows the presence of Fe, O, Si, Ca, Al, K, and Mg, indicating mainly oxides of iron and some contamination from the atmosphere. The same sample upon exposure in soil forms Fe-chlorides and Fe-oxides as shown in Fig. 5(a) and (b). Although XRF and XRD analyses of the corrosion products do not indicate the presence of any chloride compound, the SEM/EDS analysis showed that chloride ion is taking an important part in corrosion of mild steel coupons in soil. The SEM/EDS results show that the coupons were covered with mainly oxides and chlorides of iron with small amounts of SiO_2. The chloride compounds formed on iron and steel specimens are soluble in water and most probably converted into oxides and oxyhydroxides. This could explain the absence of chlorides in XRF and XRD results. For this reason, probably, small amounts of chlorides retained only at localized regions could be detected using SEM/EDS analysis which is capable of detecting elemental constitution at a micro level. The morphology of corrosion product formed after exposure to splash zone conditions is shown in Fig. 6(a) and the EDS spectrum in Fig. 6(b) indicates the presence of Ca- and Mg-based compounds that might have been formed due to microorganisms in the seawater.

The morphology of corrosion products formed in three different environments on bare steel rebar and galvanized steel coupon is shown in Fig. 7(a)-(c) and 8(a)-(c), respectively. Bare alloy formed mainly Fe-oxides while Zn coated samples

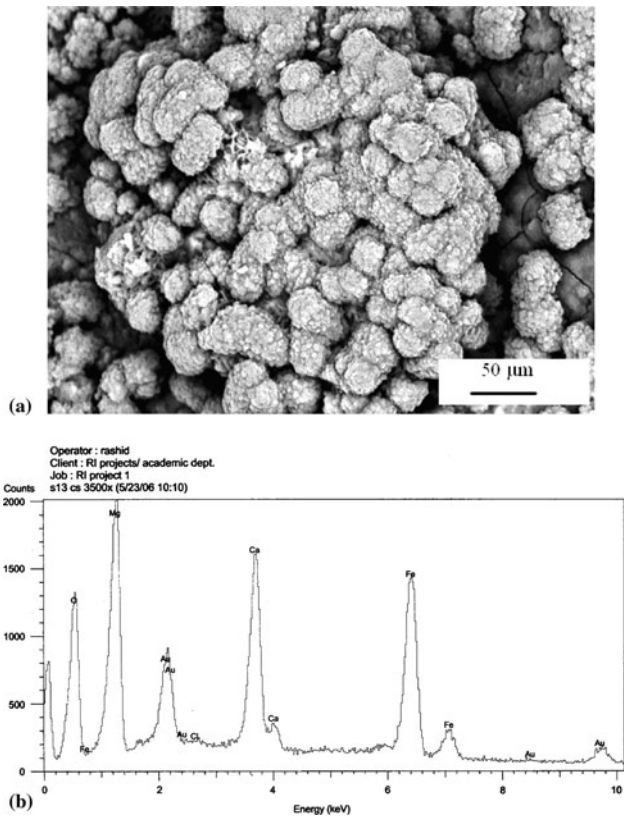

Fig. 6 (a) SEM micrograph of mild steel coupon exposed to the splash zone environment. (b) EDS spectrum obtained from the sample surface showing the presence of Fe, Ca, Mg, and O

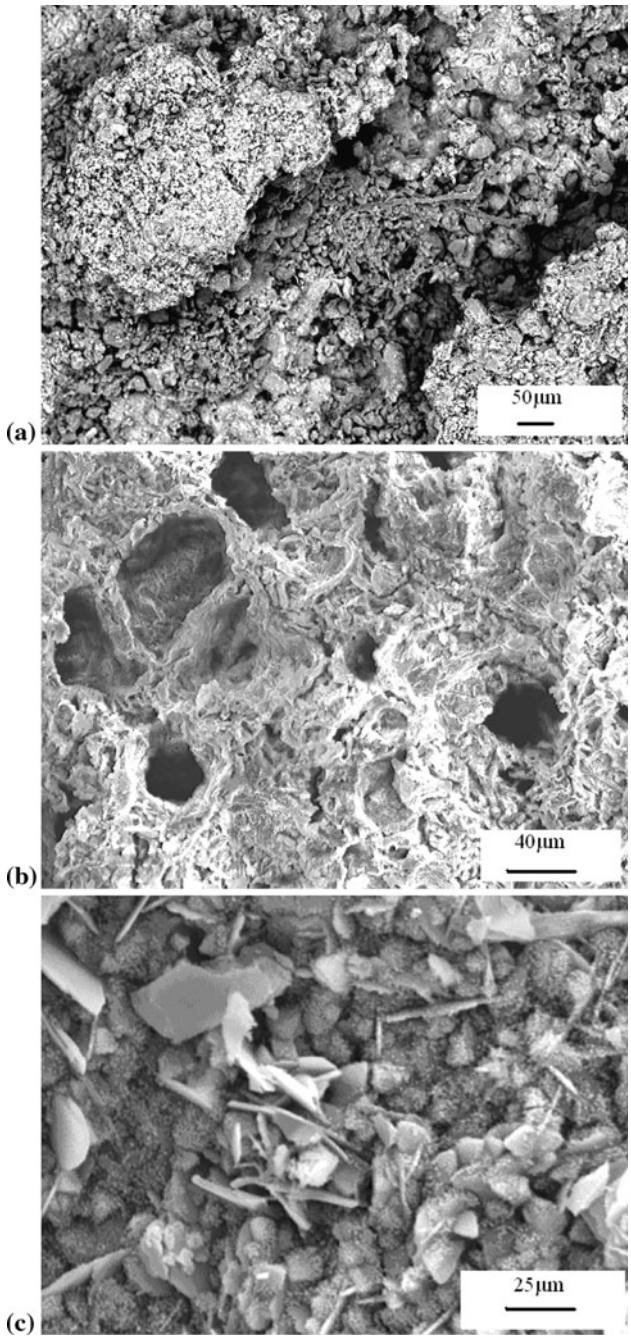

Fig. 7 Surface morphology of the corrosion product formed on bare mild steel bar sample exposed to (a) atmosphere, (b) soil, and (c) splash zone environments

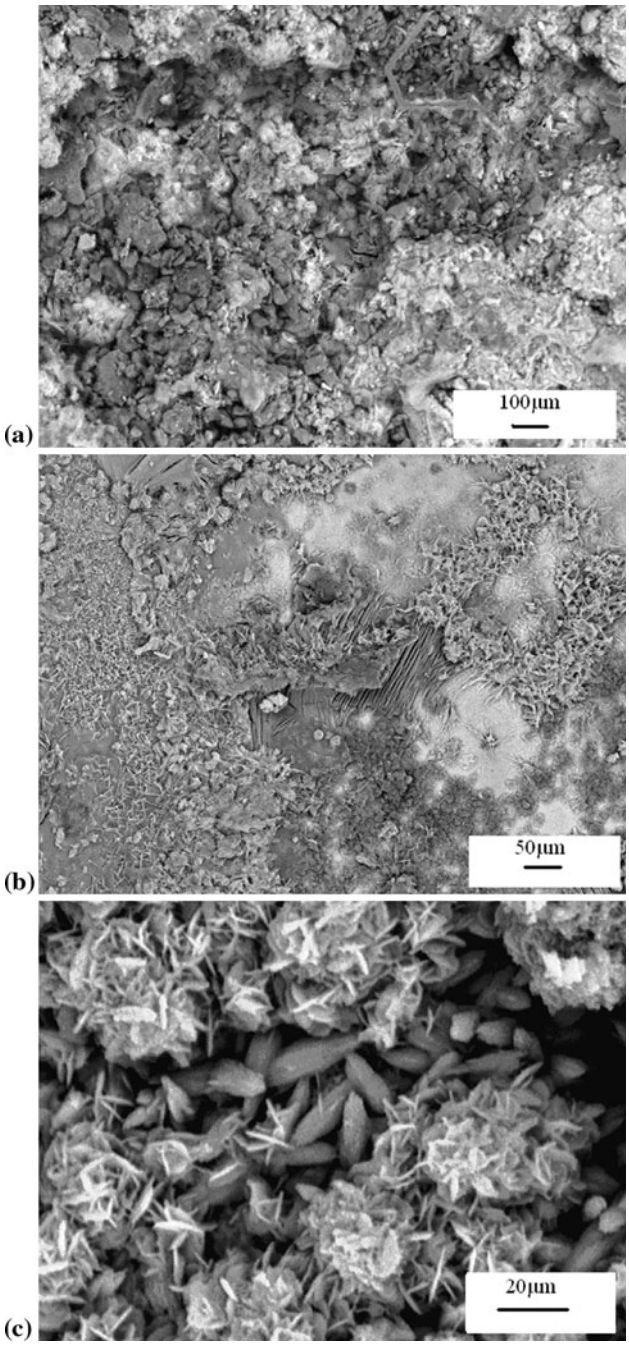

Fig. 8 Surface morphology of the corrosion product formed on galvanized mild steel coupon exposed to (a) atmosphere, (b) soil, and (c) splash zone environments

Table 7 Average corrosion rates of mild steel samples in atmospheric, soil, and splash zones

	Average corrosion rate, μm/year			
Material	**Atmosphere**	**Soil**	**Splash zone**	**Ratio**
Mild steel coupon	26.3	208.7	493.2	1:8:19
Mild steel rebar	38.0	277.5	1704.8	1:7.3:45
Galvanized mild steel	5.5	16.2	216.3	1:3:39
Ratio	1:7:5	1:17:13	1:2.3:8	

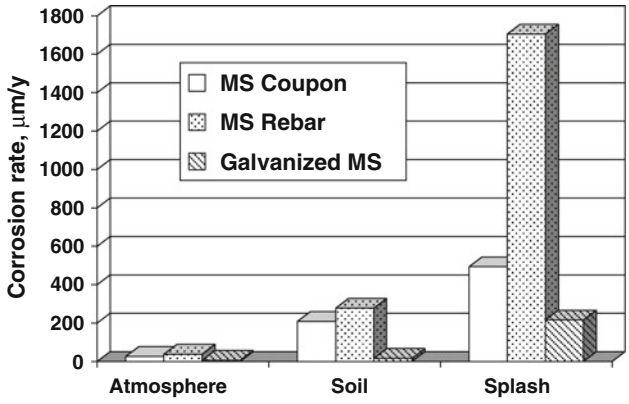

Fig. 9 Average corrosion rates of mild steel samples measured in three different exposure conditions

produced Zn-based corrosion products along with Fe-oxides. Exposure of galvanized steel to the splash zone conditions resulted in the complete rusting and removal of Zn coating.

In summary, the experimental results suggest that the corrosion product formed on all mild steel samples was mainly Fe-oxides and their hydrated forms. The Zn coating on the galvanized sample formed Zn-based compounds while contaminants such as Cl, Ca, Mg, Si, etc., were observed for all environments.

3.6 Corrosion Rates

The average corrosion rates of mild steel samples exposed to atmospheric, soil, and splash zone conditions are shown in Table 7 and also compared in the bar chart shown in Fig. 9. The average corrosion rate of the mild steel tested was 26.3, 208.7, and 493.2 μm/year in atmosphere, soil, and splash zone, respectively. The corrosion rate of the steel rebar was higher than the plate samples in all the environments probably due to shape and production factors. It was 38.0, 277.5, and 1,704.8 μm/year in atmosphere, soil, and splash zone, respectively. The corrosion rates of the steel bars are 1.44, 1.33, and 3.46 times higher than mild steel plates in atmosphere, soil, and splash zone, respectively. Galvanized steel corroded at the rate of 5.5, 16.2, and 216.3 μm/year in atmosphere, soil, and splash zone, respectively. The corrosion rate of galvanized steel was much less than corrosion rates of bare mild steel coupons. It was 5-7 times less in atmosphere, 13-17 times less in soil, and 8-23 times less in splash zone. It is clear from the results that the atmospheric environment was the least corrosive of the three environments and the splash zone was the most corrosive to all the samples tested. The corrosion rate of mild steel was 8-19 times, rebar 7.3-45 times, and galvanized steel 3-39 times higher in soil and splash zone, than the corrosion rates in atmosphere.

The data in Table 8 and 9 were compiled from available literature and show corrosion rate of bare and galvanized steel in atmosphere, soil, and splash zone environments in different parts of the world. Table 10 compares research results with the reported data in Table 8 and 9. It is clear in Table 10 that the atmospheric corrosion rate for both bare mild steel and galvanized steel is comparable to the values reported for other parts of the world. On the other hand, the soil and splash zone corrosion rates found for the materials tested in this study are much higher than the reported data, indicating more corrosive soil and splash zone at KMTS.

Table 8 Corrosion rate of bare and galvanized mild steels in different parts of the world

City/country/location	Corrosion rate, μm/year			References
	Mild steel plate	Seel rebar	Galvanized mild steel	
South Africa				
Walvis Bay, Severe Marine	110	…	63 (Zn)	
Philippines				
Manila, Tropical Marine	51	…	…	16
Spain				
Madrid	43.7	…	…	17
Barcelona	39.0	…	…	
France				
Splash Zone Salins de Girand 25 year average	190	…	…	18
Finland				
Harmaja Marine	…	…	1.2 molten Zn	19
UK				
London, Battersea, Industrial	…	46	3.6 (Zn)	16
Dungeness, Industrial Marine	…	490	…	20
Poland				21
Chorzow, Industrial	…	…	4.8	
Warsaw, Urban	…	…	2.6	
Gdynia, Marine	…	…	2.1	
Brwinow, Rural	…	…	1.2	
Norway				
Sogan	21.6	…	…	22
Bergen-Veritas	34.2	…	…	
Sapsborg-Borregaard	69.7	…	…	
Panama				
Miraflores Inland	38-43	…	…	…
Cristobal Seacoast	66	…	2.6 (Zn)	16, 19
Galeta Point Beach	686	…	15 (Zn)	20
Arjantine				
Rio de Janeiro	184.8	…	…	23
Canada				
Montreal, Quebec, Canada, Urban	23	…	…	16
USA				
Phoenix, AZ, Rural Arid	4.6	…	…	16
Pittsburgh, PA, Industrial	30	…	3.03	16
East Chicago, IN, Industrial	84	…	6.4 (Zn)	16, 24
Kure Beach, NC (beach), Marine	533	…	…	16, 24
Cape Kennedy, FL (beach)	1070	…	4.4 (Zn)	20

Table 9 Corrosion rate of bare and galvanized mild steels in different soils and splash zones of the world

Environment	CR, μm/year		References
	Besemer steel	GS pipe (2.8 oz Zn/sqft)	
Exposure in soil			
Everett gravelly sandy loam	…	0.5	25, 26, 31, 33
Miami silt loam	…	1.3	25, 26, 31, 33
Cecil clay loam	…	1.6	25, 26, 31, 33
Fargo silt loam	…	2.9	25, 26, 31, 33
Average of 44 soils	20.9	…	15, 34
Tidal Marsh, Elizabeth, NJ	90.6	…	15, 34
Montezume clay, Adobe, San Diego, CA	66.4	…	15, 34
Merrimac gravelly sandy loam, Norwood, MA	4.7	…	15, 34
	Steel	**GS plate**	
Exposure in splash zone			
Steel with mill-scale, Southampton, UK	44.0	27.9	25, 27, 30, 32
Steel pickeled, Plymouth, UK	107.6	…	25, 28, 32
Steel sand-blasted, Pacific Ocean, Panama	332.1	…	25, 29, 32

CR, corrosion rate, μm/year; GS, galvanized steel

Table 10 Comparison of corrosion rates

	Data from this research, μm/year		Data from literature, μm/year	
Environment	**Bare steel**	**GS**	**Bare steel**	**GS**
Atmosphere	26-38	5.5	4.6-1070	1.2-63
Soil	209-278	16	4.7-90.6	0.5-2.9
Splash zone	493-1705	216	44-332	27.9

4. Conclusions

Environmental parameters showed that atmosphere, soil, and splash zones were all corrosive to bare mild steel. The main parameters resulting in atmospheric corrosive conditions were high chloride and sulfate concentrations as well as temperature and humidity variations. The soil and groundwater were also high in chloride and sulfate contents which render underground environment corrosive. Bacterial activity in the soil might have also contributed to increased corrosivity in this environment. However, no specific investigation was carried out to confirm this point. The splash zone was affected from high chloride concentration in seawater as well as intermittent wetting-drying cycles, which make the zone severely corrosive. The splash zone was the most corrosive of the three environments studied in this paper. The corrosion rate of mild steel was several orders of magnitude higher in the splash zone compared to the atmosphere.

Comparison of the corrosion rates of mild steel in Khaleej Mardumah test station, Jubail, Saudi Arabia, with the corrosion rates in other parts of the world shows that the atmosphere in Jubail is significantly corrosive. The soil environment and splash zone, however, are very corrosive to bare steel and galvanized steel samples tested. The experimental results clearly indicate that the conventional mild steel should not be used in atmospheric, soil, and seawater applications without adequate corrosion protection such as coatings or cathodic protection.

Acknowledgments

The authors acknowledge the support of Research Institute of King Fahd University of Petroleum & Minerals and Royal Commission for Jubail and Yanbu, Directorate General of Jubal Project.

References

1. I.M. Allam, J.S. Arlow, and H. Saricimen, Initial Stages of Atmospheric Corrosion of Steel in the Arabian Gulf, *Corros. Sci.*, 1991, **32**, p 417–432
2. H. Saricimen, Research to Improve Durability of Reinforced Concrete in Aggressive Environments, *Proceedings of the International Seminar on Controlling Concrete Degradation*, University of Dundee, Scotland, UK, 7 Sept 1999, p 101–113
3. KFUPM-RI, Final Report, Soil Corrosivity Study, Contract No. 001-T20, KFUPM, Research Institute, Dhahran, Saudi Arabia, 1981
4. KFUPM-RI, Final Report, PN25016/Pilot Audit, Corrosion Control and Monitoring at Madinat Al-Jubail Al-Sinaiyah, KFUPM, Research Institute, Dhahran, Saudi Arabia, 1985
5. K. Barton, *Protection Against Atmospheric Corrosion: Theories and Methods*, Vol 3, Wiley, London, 1976
6. P.W. Brown and L.W. Masters, Factors Affecting the Corrosion of Metals in the Atmosphere, *Atmospheric Corrosion*, W.H. Ailor, Ed., Wiley, New York, 1982, p 37
7. J.R. Duncan, Corrosion in the Atmosphere, *Proceedings of the First Arabian Conference on Corrosion*, Kuwait, February 4–8, 1984
8. D. Fyfe, Metal/Environment Reactions, *Corrosion*, Chap. 2.2, L.L. Shreir, Ed., Newnes-Butterworths, London, 1976
9. F.P. Miller, J.E. Foss, and D.C. Wolf, Soil Surveys: Their Synthesis, Confidence Limits, and Utilization for Corrosion Assessment of Soil, *ASTM Special Technical Publication*, 1981, Vol 741, p 3–23
10. U.S.D.A., *Guide for Interpreting Engineering Uses of Soils*, US Department of Agriculture, Soil Survey Staff, US Government Printing Office, Washington DC, 1971
11. B.D. Craig and D.S. Anderson, Ed., *Handbook of Corrosion Data*, ASM International, Materials Park, OH, 1995, p 822–823
12. ASTM G50, Standard Recommended Practice for Atmospheric Corrosion Tests on Metals and Alloys, *Annual Book of ASTM Standards*, Vol 3.02, American Society for Testing and Materials, Philadelphia, 1989
13. ASTM G1, Recommended Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens, *Annual Book of ASTM Standards*, Vol 3.02, American Society for Testing and Materials, Philadelphia, 1988
14. ASTM G46, Standard Guide for Examination and Evaluation of Pitting Corrosion, *Annual Book of ASTM Standards*, Vol 3.02, American Society for Testing and Materials, Philadelphia, 1988
15. D.A. Jones, *Principles and Prevention of Corrosion*, Prentice-Hall, Upper Saddle River, NJ, 1996
16. M.J. Johnson and P.J. Pavlik, Atmospheric Corrosion of Stainless Steel, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 461
17. S. Feliu and M. Morcillo, Atmospheric Corrosion Testing in Spain, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 914
18. M.A. Lashermes, M. Rebaul Guilhaudis, and G. Tentelivres, Third Year Atmospheric Corrosion of Aluminum Alloys in France, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 353
19. C.R. Southwell and J.D. Bultman, Atmospheric Corrosion Testing in the Tropics, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 943
20. A.P. Castillo and J.M. Popplewell, General, Localized, and Stress-Corrosion Resistance of a Series of Copper Alloys in Natural Atmospheres, *Atmospheric Corrosion in Metals*, ASTM Special Technical Publication 767, S.W. Dean, Jr. and E.C. Rhea, Ed., American Society for Testing and Materials, 1982, p 60–84
21. T. Bietek, Testing of Electrodeposited Zinc and Cadmium Coatings, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 631
22. Corrosion Rate of Carbon Steel, *Metals Handbook*, ASM Vol 1, 9th ed., p 72, 723, 1987
23. L. Atteraas and S. Haagenrud, Atmospheric Corrosion in Norway, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 873
24. R.A. Legault. Atmospheric Corrosion of Galvanized Steel, *Atmospheric Corrosion*, Corrosion Monograph Series, W.H. Ailor, Ed., The Electrochemical Society, Inc., Princeton, NJ, 1982, p 607
25. H.H. Uhlig, Ed., *The Corrosion Handbook*, Wiley, NY, 1948
26. K.H. Logan and M. Romanof, Soil Corrosion Studies, 1941. *J. Res. Natl. Bur. Stand.*, 1944, **33**, p 145 (R.P. 1602)
27. N.J. Friend, The Relative Corrosivities of Ferrous and Non-Ferrous Metals and Alloys, Part III, *J. Inst. Met.*, 1932, **48**(1), p 109
28. Deterioration of Structures in Seawater, 18th Report of the Committee of the Institution of Civil Engineers, London, 1938
29. Unpublished Data from International Nickel Co., Inc., New York, NY
30. Deterioration of Structures in Timber, Metal, and Concrete Exposed to the Action of Seawater, 15th Report of Committee of Institution of Civil Engineers, London, 1935
31. K.H. Logan and S.P. Ewing, Soil Corrosion Studies, 1934. *J. Res. Natl. Bur. Stand.*, 1937, **18**(361) (R.P. 982)
32. F.L. LaQua, Behavior of Metals and Alloys in Sea Water, *The Corrosion Handbook*, H.H. Uhlig, Ed., Wiley, New York, 1948, p 353
33. K.H. Logan, Corrosion by Soils, *The Corrosion Handbook*, H.H. Uhlig, Ed., Wiley, New York, 1948, p 446–466
34. H.H. Uhlig and R. W. Revie, *Corrosion and Corrosion Control*, 3rd ed., Wiley, New York, 1985, p 182