Atmospheric Corrosion Performance of Engineering Materials in India

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The atmospheric corrosion map of India has been updated with data from 57 exposure sites throughout the country, covering rural, urban, industrial, and marine conditions. Mild steel, zinc, galvanized iron, and aluminum were exposed to the different conditions over a period of four years. This article presents data gathered from 15 test sites.

Industrial growth during the last decade has made it necessary to evaluate installations, equipment, and metallic and nonmetallic structures exposed to the atmosphere. The atmosphere has also become more contaminated and therefore more aggressive to materials exposed to an enormous quantity of gases.

India has mainly three seasons in a year: rainy (June through September, southwest monsoon, and October through November, northeast monsoon), summer (April through July), and winter (mid-October through February). The country has a coastline of more than 7,500 km, the reason for the high airborne salinity in many areas. The air quality in big cities has decreased significantly. A variety of industrial processes, such as the production of iron and steel, utility factories, and crude oil processing, pollute the atmosphere by the release of sulfur dioxide (SO_2). SO_2 can also be emitted by natural disasters or means such as volcanoes, sea spray, plankton, and rotting vegetation. Overall, 69.4% of SO_2 is produced by industrial combustion and >90% of the sulfur in the atmosphere is of human origin.[1]

Steel, zinc, galvanized metals, and aluminum are found to be very sensitive to acidic pollutants, especially SO_2 and acid rains.[2] No systematic research on atmospheric corrosion of the steel and other metals has been done in India. Before 1970, little quantitative atmospheric corrosion data had been published in India.[3] More recently, results from several studies have been reported.[4-7] Ramana, et al.[8] have reported the characterization of rust phases formed on low carbon steel exposed to a natural marine environment.

We made a study on the kinetics of atmospheric corrosion of mild steel (MS), zinc, galvanized iron (GI), and aluminum at 10 exposure stations in India[9] and the

TABLE 1

The location and characteristics of the exposure sites in India

Site No.	Site	Type	Latitude	Longitude	Prominent Features
1	Chandigarh	Urban	30°.74'	76°.79'	A research institute site in the center of a residential area 5 km from the city center
2	New Delhi	Urban	28°.6'	77°.2'	A research institute site at the top of a two-story building
3	Aligarh	Urban	27°.4'	80°.00'	An educational institution site at the top of a two-story building
4	Bhopal	Urban	9°.96'	76°.23'	A research institute site at the top of a two-story building
5	Pune	Urban	18°.32'	72°.51'	A research institute site at the top of a single-story building
6	Hyderabad	Urban	17°.23'	78°.29'	A research institute site at the top of a two-story building
7	Warangal	Rural	17°.55'	79°.36'	An educational institution—the exposure stands were erected at ground level
8	Kolkata	Urban/ Industrial	22°.57'	88°.39'	A research institute site at the top of a two-story building
9	Bhubaneswar	Urban	20°.60'	85°.45'	A research institute site at the top of a two-story building
10	Visakhapatnam	Industrial/ Marine	17.7°	83°.3'	An industrial area alongside a transport road, 5 km from the sea
11	Pondicherry	Marine	11°.92'	79°.95'	An educational institution site at the top of a two-story building
12	Karaikudi	Rural	10°.40'	78°.47'	A research institute site at the top of a single-story building
13	Kanyakumari	Rural/Marine	8°.35'	77°.36'	A college site at the top of a two-story building
14	Kochi	Marine	22°.57'	88°.37'	A naval base site 50 m from the Arabian seacoast
15	Kalamassery	Urban/Industrial	22°.57'	88°.37'	A research institute site at the top of a two-story building

results were compared with global levels. In continuation of this work, the present program was undertaken and the results obtained on MS, Zn, GI, and Al corrosion in natural atmospheres are reported. The results are discussed as a function of exposure time and pollution levels.

Experimental Procedures

Exposure sites were chosen according to the local atmosphere, convenience of installation, and facilities for technical assistance. Table 1 gives the location of the test sites. The composition of the materials utilized in the present research are reported in an earlier publication.[8] Before exposure, the specimens (100 by 150 mm) were polished with 120 grade emery wheel and degreased with trichloroethylene (C_2HCl_3), dried, and weighed with a precision of 0.1 mg. Metal specimens 2.5-mm thick were exposed for one to two years, and 4-mm thick specimens were exposed for more than two years. The exposure angle was 45 degrees facing the south. The corrosion rates were evaluated by the weight loss method. The corrosion rate was determined by considering the total affected area facing the sky and the ground, metal density, and exposure time. The corrosion rates were determined by the following equation:

$$\text{Corrosion rate } (\mu m/y) = \frac{87,600 \times W}{A \times T \times D} \qquad (1)$$

where W = weight loss (mg), A = area of the specimen (cm^2), D = density of the specimen (gm/cm^3), T = time (h), and µm/y = micrometer/y.

Corrosion products were removed by using the respective pickling solution.[10] Guidelines from IS 5555,[11] ISO 9225,[12] and ASTM G50-76[9,13] were used for the exposure and cleaning procedures required before exposure and for cleaning and evaluation after the exposure.

In atmospheric corrosion studies, the determination of the concentration of

TABLE 2

Annual average maximum and minimum values of temperature, RH, and rainfall at the exposure sites

Site No.	Test Site	Annual Temperature (°C)		RH (%)		Rainfall (mm)
		Maximum	Minimum	Maximum	Minimum	
1	Chandigarh	39	7	91	58	269
2	New Delhi	40	6	98	56	184
3	Aligarh	40	6	90	58	217
4	Bhopal	40	10	94	52	501
5	Pune	38	12	86	64	722
6	Hyderabad	45	14	84	58	165
7	Warangal	45	15	85	60	170
8	Kolkata	36	12	90	54	320
9	Bhubaneswar	38	16	92	55	336
10	Visakhapatnam	38	18	95	61	327
11	Pondicherry	36	21	85	60	435
12	Karaikudi	33	21	80	65	180
13	Kanyakumari	34	22	87	58	89
14	Kochi	32	23	99	54	592
15	Kalamassery	32	22	95	50	580

TABLE 3

Annual average for deposition rate (first year) value of chloride and SO_2, environmental, and corrosivity categories classification according to ISO 9223

Site No.	Test Site Name	Chloride (mg/m²·day)	SO_2 (mg/m²·day)	Environmental Category		Corrosivity Category Based on First Year Data			
				(Cl⁻)	SO_2	MS	GI	Zn	Al
1	Chandigarh	11.3	Traces	S1	P0	C2	C3	C3	C2
2	New Delhi	Traces	10	S0	P1	C2	C4	C2	C2
3	Aligarh	7.00	20	S1	P1	C2	C4	C4	C2
4	Bhopal	15.06	Traces	S1	P0	C1	C1	C2	C2
5	Pune	7.63	34	S1	P1	C2	C4	C3	C2
6	Hyderabad	11.44	Nil	S1	P0	C2	C4	C4	C2
7	Warangal	Traces	Nil	S0	P0	C2	C2	C3	C2
8	Kolkata	16.33	19	S1	P1	C2	C3	C3	C2
9	Bhubaneswar	13.19	8	S1	P0	C2	C3	C3	C3
10	Visakhapatnam	14.44	13	S1	P1	C3	C4	C4	C4
11	Pondicherry	22.00	11	S1	P1	C3	—	C3	C2
12	Karaikudi	23.06	Traces	S1	P0	C2	C2	C3	C2
13	Kanyakumari	23.06	Nil	S1	P0	C2	C4	C3	C4
14	Kochi	49.60	31	S1	P1	C5	C5	C5	C3
15	Kalamassery	31.40	31	S1	P1	C5	C4	C4	C2

pollutants dissolved in the air, mainly SO_2 and salinity (chloride), constitute a basic requirement. Climatic parameters including meteorological variables and pollution levels such as salinity and SO_2 were measured using ASTM D2010.[14] SO_2 of the atmosphere was absorbed by lead dioxide (PbO_2) and was transformed into $PbSO_4$, which was analyzed by the gravimetric method. The amount of salinity captured by the wet candles was determined by titration method. These SO_2 and salinity results, along with temperature, relative humidity (RH), rainfall, and pollutants, have been reported elsewhere.[4]

Results and Discussion

Environmental Exposure Sites

Table 1 shows the location and characteristics of exposure sites. The New Delhi, Chandigarh, Aligarh, and Pune exposure sites are located in the northern part of India. Pondicherry and Kochi, marine environments, are on the east and west coasts, respectively, of the southern part of India. Bhubaneswar and Kolkata are township environments in the northeast part of India and characterized as urban. Bhopal, located at the central part of India, is a rural environment. The Visakhapatnam site is located 5 km away from the east coast, and Karaikudi and Warangal are rural environments. Kalamassery is a township area with surrounding small industries. The Hyderabad exposure site is located in a township area with vehicle transportation. Kanyakumari is at the tip of India, where the three seas (Bay of Bengal, Indian Ocean, and the Arabian Sea) meet. The exposure site at Kanyakumari is 3 km away from the sea coast and surrounded by coconut trees.

Table 2 shows that the maximum temperatures range from 32 to 45 °C, whereas the minimum temperatures were 7 to 23 °C. The maximum RH was the highest in Kochi (99%) and lowest in Karaikudi (80%). The lowest minimum RH (50%) was observed at Kalamassery whereas Karaikudi recorded 65%. The maximum rainfall of 435 mm was observed in Pondicherry whereas Kanyakumari received a minimum rainfall of 89 mm.

An average annual deposition rate of salinity and SO_2 pollutants, and the corrosion rates of four materials (Table 3) during the first year, were used for the classification of the pollution and the corrosivity category of materials. According to ISO 9223,[15] deposition rates of effective SO_2 and airborne salinity represented by chloride were determined monthly and continuously using the lead peroxide and wet candles procedures, respectively. The chloride and SO_2 levels (in mg/m^2 day) in the atmosphere were classified as S_0, S_1, S_2, S_3, and P_0, P_1, P_2, P_3, respectively. The first category represents a pollution deposition rate value that is insignificant from the point of view of corrosive attack. Categories 1, 2, and 3 are considered as significant, medium, and extreme.

Corrosion products are formed on the exposed surfaces. The rate of corrosion is obtained by the characteristics of the rust products, the presence of an electrolyte film, and the composition of the electrolyte, which is largely related to the deposition rate of the atmospheric pollutants—mainly SO_2 and salinity in the industrial, urban, and coastline regions. Based on corrosion rate, ISO 9223 uses the following categories: C1 (very low corrosivity), C2 (low corrosivity), C3 (medium corrosivity), C4 (high corrosivity), and C5 (very high corrosivity).

Table 4 gives the corrosion data of four materials in different exposure sites for durations of one to three years, and data for four years are also given for certain locations. The values of the corrosion rate of the metals are used to classify the corrosive atmosphere, since the classifications patterns given by the ISO norm depend on metal.

Table 3 shows the classifications of the corrosion rate of the metals based on the first-year data. The determination of corrosion rates by the weight loss method provides the most reliable picture concerning the aggressiveness of a given atmosphere, so the corresponding corrosion rates approach service conditions more than any other method. The corrosion rates observed in sites that are marine, urban, and rural in nature are similar to those obtained by other authors for highly aggressive geographic areas.[16] The salinity and SO_2 are found to be the main factors influencing the process of corrosion.

Tables 3 and 4 show that the corrosion rate for mild steel at Kochi and Kalamassery are very high (C5). At the Visakhapatnam and Pondicherry sites, medium corrosion rates were observed (C3). At all other exposure sites, except Bhopal, the corrosion rates observed were low (C2), whereas the corrosion rate at Bhopal was very low (C1). This could be due to lower chloride and only traces of SO_2 pollutant levels, so the site is designated as a category S_1 P_0 atmosphere. In Kochi and Kalamassery, the observed values correspond to the atmospheric environmental category S_1 P_1 with heavy rainfalls and high RH. Other exposure sites are classified as category S_0, S_1, and P_0, P_1 pollution levels.

Results

Mild Steel

Table 4 and Figure 1(a) show that the corrosion rates of MS decreased during exposure and the corrosion rates of other metals show fluctuations. The highest corrosion rate (C5) was observed at the Kochi and Kalamassery exposure sites, whereas the lowest rate (C1) was observed at Bhopal. The corrosion rates were decreased with exposure time, perhaps by the formation of adherent corrosion products on the surface.

Zinc

Table 4 and Figure 1(b) show the corrosion rate for Zn. The Kochi site was in the highest corrosion rate (C5). The highest as well as the lowest corrosion rate of Zn is very much lower than that of MS. The corrosion rate of Zn increased with exposure time. This may be due to the presence of the basic salt layers on the Zn that would be transformed into more water-soluble layers, offering significantly less corrosion protection.

Galvanized Iron

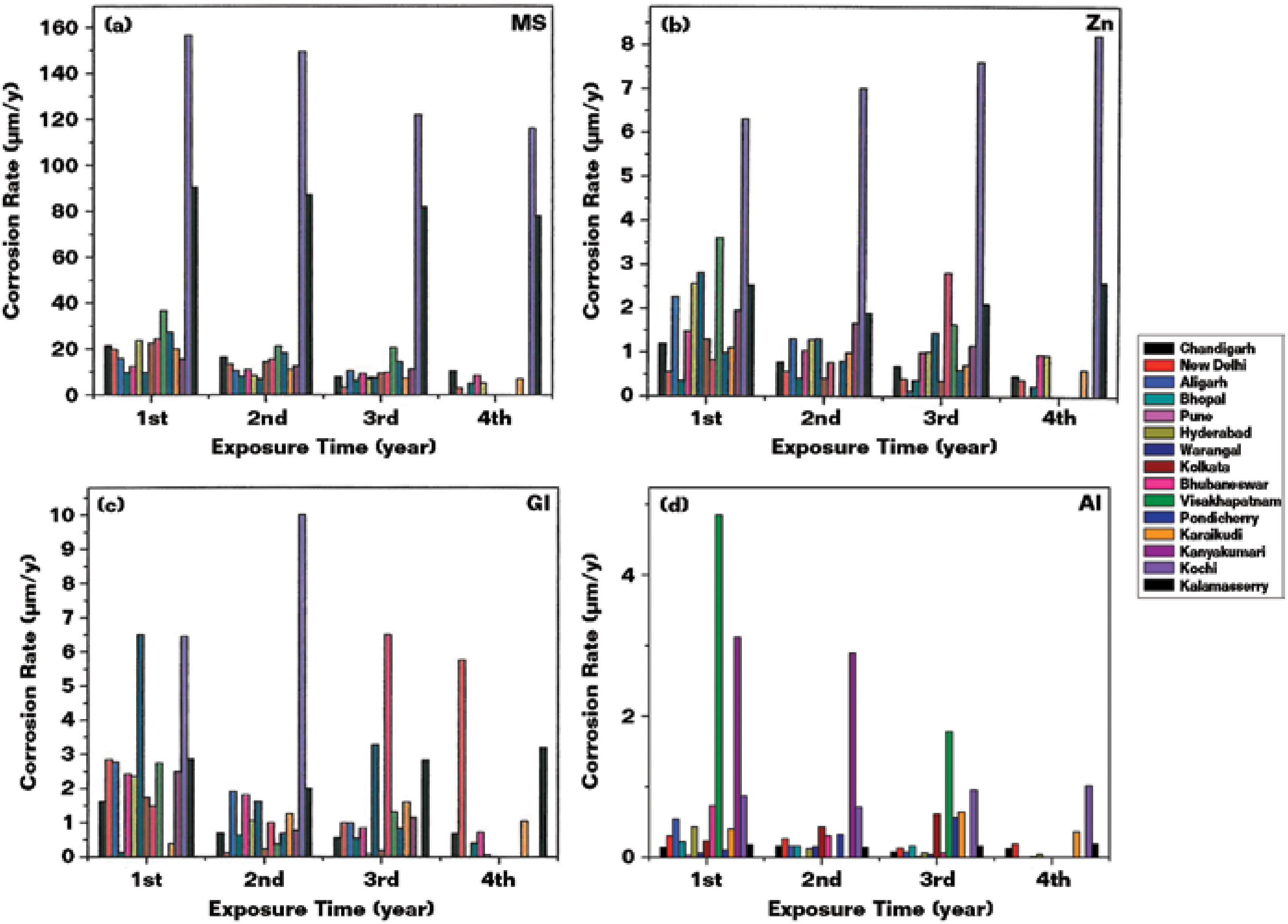
Table 4 and Figure 1(c) show the corrosion rate for GI. The corrosivity

TABLE 4

Corrosion rates of MS, Zn, GI, and Al in different exposure sites

No.	Test Site	Period Year	Corrosion Rate (μm/y)			
			MS	Zn	GI	Al
1	Chandigarh	1	21.44	1.2	1.62	0.14
		2	16.36	0.78	0.70	0.16
		3	7.82	0.69	0.56	0.07
		4	10.51	0.47	0.69	0.12
2	New Delhi	1	19.77	0.56	2.85	0.30
		2	13.25	0.57	0.11	0.26
		3	3.19	0.4	1.0	0.13
		4	2.99	0.38	5.76	0.19
3	Aligarh	1	15.90	2.26	2.78	0.54
		2	10.52	1.30	1.90	0.16
		3	10.50	0.12	0.99	0.07
4	Bhopal	1	9.82	0.36	0.12	0.22
		2	7.99	0.41	0.62	0.16
		3	6.20	0.37	0.54	0.16
		4	4.97	0.24	0.41	—
5	Pune	1	12.40	1.48	2.42	0.03
		2	11.03	1.039	1.805	—
		3	9.16	1.0	0.84	0.01
		4	8.33	0.96	0.72	0.01
6	Hyderabad	1	23.51	2.56	2.36	0.43
		2	8.26	1.28	1.06	0.12
		3	6.79	1.02	0.09	0.06
		4	5.15	0.94	0.06	0.04
7	Warangal	1	9.84	2.81	6.50	0.058
		2	6.90	1.30	1.62	0.15
		3	7.25	1.45	3.28	0.04
8	Kolkata	1	22.60	1.29	1.75	0.23
		2	14.40	0.41	0.22	0.43
		3	9.61	0.36	0.18	0.61
9	Bhubaneswar	1	24.40	0.83	1.49	0.73
		2	15.43	0.77	1.00	0.30
		3	9.84	2.81	6.50	0.06
10	Visakhapatnam	1	36.69	3.6	2.75	4.85
		2	21.15	—	0.37	—
		3	20.62	1.64	1.31	1.78
11	Pondicherry	1	27.42	0.99	—	0.10
		2	18.28	0.80	0.68	0.32
		3	14.64	0.61	0.83	0.56
12	Karaikudi	1	19.97	1.10	0.381	0.40
		2	10.948	0.9939	1.25	—
		3	7.26	0.72	1.60	0.64
		4	6.86	0.61	1.05	0.36
13	Kanyakumari	1	15.64	1.96	2.49	3.12
		2	12.50	1.67	0.77	2.89
		3	11.27	1.16	1.15	—
14	Kochi	1	156.60	6.30	6.45	0.87
		2	149.30	7.0	10.02 (Zn	0.71
		3	121.9	7.6	coating partly	0.95
		4	116.0	8.2	eaten away)	1.01
15	Kalamassery	1	90.50	2.53	2.86	0.18
		2	87.0	1.9	2.0	0.14
		3	81.9	2.1	2.83	0.16
		4	78.0	2.6	3.20	0.19

FIGURE 1



Corrosion rate as a function of exposure time for (a) MS, (b) Zn, (c) GI, and (d) Al.

category for GI is C5 in the marine atmosphere at Kochi. The acceleration is caused by the high salt content and SO_2 content at this site. The higher corrosion rate (C4) was observed at Kalamassery, Kanyakumari, Visakhapatnam, Hyderabad, Pune, Aligarh, and New Delhi. The medium corrosion rate (C3) was observed in Bhubaneswar, Kolkata, and Chandigarh. The low corrosion rate (C2) was observed at Warangal and Karaikudi. There has been little corrosion progression over the four years at almost all the sites except Kochi. The highest corrosion rate for GI indicated that after 1 1/2 years, the GI panels (Figure 2) were completely corroded because of the presence of high chloride deposition on the metal surface. Table 4 shows that the corrosion rate of GI is greater than that of zinc. This may be caused by the galvanic action of Zn on the GI.

Aluminum

At all sites, Al showed a very low corrosion rate in comparison with MS, Zn, and GI. The Visakhapatnam and Kanyakumari sites were found to be C4 corrosivity categories (Table 4 and Figure 1[d]).

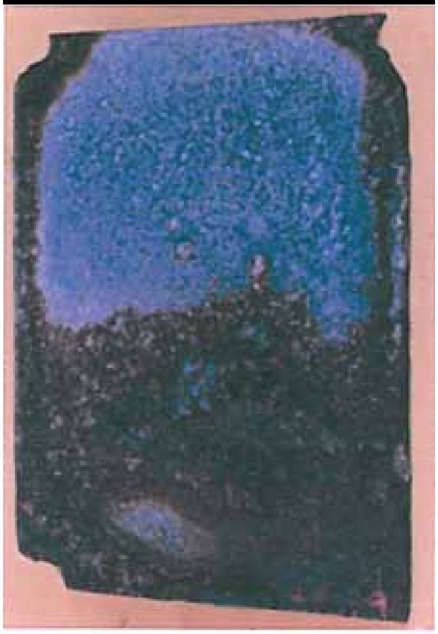
Summary

Table 4 also shows that the corrosion rate depends on the nature of the material. Generally, higher corrosion rates were obtained for MS and the lower one for Al. The corrosion rates varied from one site to another. The maximum corrosion rate of 156.6 μm/y was observed at Kochi followed by Kalamassery (90.5 μm/y). Other coastal areas, such as Pondicherry, also exhibit medium corrosion rate (C3) values. The corrosion rates observed at the coastal sites (Kochi and Pondicherry) are several times higher than inland sites such as Bhopal. There were marked variations in the corrosion rates of Al by location. The results for Al (Table 4) show a significantly high corrosion rate at the Kanyakumari site compared to the other 14 locations with respect to time. As a result, the corrosion rates of test materials in different atmospheres were found to be in the order of MS > GI > Zn > Al.

Conclusions

Over one to four years, MS, Zn, GI, and Al metals were exposed to different atmospheres at 15 exposure sites in India.

FIGURE 2



GI panel exposed at Kochi Naval Base over a period of 1.5 years.

The deposition rates of SO_2 and salinity have also been determined at each exposure site. The SO_2 rates for the first year of the exposure were found to be <10 $mg/m^2/day$ (low) at Chandigarh, Bhopal, Hyderabad, Warangal, Bhubaneswar, Karaikudi, and Kanyakumari; and significant values (10 to 31 $mg/m^2/day$) were found at the remaining sites. Salinity values, however, were significant at 13 sites and at the remaining two sites (New Delhi and Warangal), the values were found to be lower. The corrosion rates of test materials in different atmospheres were found to be in the order of MS > GI > Zn > Al. The corrosion rates observed at the coastal sites (Kochi and Pondicherry) are several times higher than inland sites like Bhopal.

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