A Novel Approach to Updating the Corrosiveness Maps of India

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ABSTRACT

Atmospheric corrosion behavior of engineering materials, viz., carbon steel, zinc, galvanized steel, and aluminium, has been studied over a period of one year at 41 exposure sites in India using weight-loss methods. Deposition rates of salinity, sulfur dioxide, and climatic variables were determined. Using these data, Indian maps of atmospheric corrosion for carbon steel, zinc, galvanized steel, and aluminum were constructed using pie charts to report results, where the diameter of the pie represents the corrosion rate of the material in each area and the size of the pie portions represent the effect of each variable in the atmospheric corrosion process.

KEY WORDS: aluminum, atmospheric corrosion, carbon steel, corrosion maps, galvanized steel, India, zinc

INTRODUCTION

Atmospheric corrosion of metals in a particular area or location is important, and these data are useful for design engineers to select suitable metals and coatings. Different countries have been using different techniques to determine the atmospheric corrosion rate using parameters such as atmospheric pollutants, wind directions, distance from the coast, salinity, temperature, rainfall, relative humidity, etc. Countries such as Canada, Sweden, the United States, New Zealand, Taiwan, Japan (the country with the most corrosive environment), and France have prepared their own maps to show their testing sites for atmospheric corrosion. Places like Australia, Africa, America, and Northern Bohemia had adopted the method of interpolation to find the atmospheric corrosion rate, using maximum to minimum testing sites. Rate maps have been produced for a number of geographic regions, illustrating the macroscopic variations in the atmospheric corrosiveness. Different methods of showing the results have been used to date. Spain presented its maps using three-dimensional (3-D) diagrams showing "corrosion/SO_2/chloride levels;" Portugal, using bar diagrams, published several maps. Similar maps have been published for Venezuela and some parts of Brazil. The Czech Republic (Northern Bohemia is a region in the Czech Republic) had published maps in the 1970s.

Researchers from Centro Nacional de Investigaciones Metalúrgicas, Ciudad Universitaria, Madrid,[1] have taken into consideration three clearly differentiated meteorological areas in Spain: the central, northwestern, and southern areas. Morales, et al.,[2] prepared two different maps: one to show the location of Canary Island (Spain) and the other to show the location of corrosion test sites at the Province of Santa Cruz de Tenerife.

In the United Kingdom,[3] the first atmospheric corrosion study of zinc was conducted in 1967, and since that time, results have been updated periodically. In 1982, a color-coded map of England and Wales, showing the background atmospheric corro-

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TABLE 1
Yearly Average Values of the Variables Under Study

Exposure Site	Temperature (°C)	Relative Humidity (%)	Rainfall (mm/y)	SO_2 (mg/m^2-d)	Salinity (mg/m^2-d)
Aligarh	23	74	217	11	20
Bhavnagar	28	73	186	—	—
Bhopal	25	73	501	Traces	24
Bhubaneswar	27	73.5	336	8	21
Chandigarh	23	74.5	269	0	18
Naval base Chennai	29.5	73.5	355	18	486
Coimbatore	30	76	240	1	20
Cuddalore	28	77	702	0	63
Dindigul	29	67	64	8	15
Hyderabad	29.5	71	165	—	18
Jorhot	25.5	75.5	686	10	22
CECRI Unit Kochi	27	72.5	580	31	50
Kakinada	27.5	75.5	320	0	121
Karaikudi	27	72.5	180	0	38
Kolkota	24	72	320	19	36
Kanyakumari	28	72.5	89	0	38
Kayamkulam	24	91	426	18	448
Lucknow	26.5	91	426	18	28
Mahendragiri	28	91.5	83	0	0
Manali	29	78.5	309	25	120
Mandapam Camp	29.5	67.5	96	0	246
Mangalore	26.5	77.5	308	Traces	110
Marumagao	25	73.5	248	22	630
Mettupalayam	27.5	89.5	22	630	Traces
Mumbai	26	73.5	945	14	48
Nagapattinam	28	70.5	750	0	29
Naval Base Kochi	27.5	76.5	592	31	79
New Delhi	23	77	184	31	79
NIO Goa	23.5	76	184	—	—
Padubidri	25.5	79	310	9	124
Pondicherry	28.5	72.5	735	11	37
Port Blair	26.5	78.5	3,028	0	356
Pune	25	75	167	12	34
Salem	30	72.5	68	0	45
Sriharikota	27.5	74	450	0	5,000
Surat	28	73	310	8	22
Tirupur	28.5	92	214	1	20
Tuticorin	28	74	90	534	59
Visakhapatnam	28	78	327	13	23
Warangal	30	72.5	170	—	—

sion rate of zinc, was first produced. The Agricultural Development Advisory Service (ADAS [Wolverhampton, United Kingdom]) produced subsequent maps incorporating both Scotland and Northern Ireland in 1986 and 1991. By 1997, there was evidence to show that sulfur dioxide (SO_2) levels in the atmosphere had fallen considerably since 1991 when the last map was produced.

The LaQue Center for Corrosion[4] (Kure Beach, North Carolina) is a pioneering institution involved in carrying out atmospheric corrosion studies. The corrosion of mild steel was studied at two sites in Singapore[5] (inland and on a raft in the sea) for three periods with two surface conditions. Corrosion of mild steel was significantly faster on the raft than inland. The long-term corrosion rates of specimens exposed to the inland marine and on the raft were found to be 0.016 mm per year for a two-year exposure and 0.659 mm per year for about 0.6 years' exposure, respectively. New Zealand,[6] South Africa,[7] China,[8] and Germany[9] have published their own corrosiveness maps. The Swedish Corrosion Institute (Stockholm, Sweden) and the State Research Institute for the Protection of Materials[10] (Prague, Czechoslovakia) have collected data for more than eight years at 11 test sites. In Australia,[11] the CSIRO Division of Building, Construction, and Engineering (Victoria, Australia) has been engaged in atmospheric corrosion mapping. The corrosiveness mapping over five years indicates that ~0.6 million dollars per year could be saved immediately by improved material selection and better maintenance planning. Mild steel and zinc metal atmospheric corrosion rate data at four sites in Vietnam[12] were collected.

TABLE 2
Criteria for Categorizing Variables from 0 to 4

Sulfur Dioxide P (mg/m^2-d)	RH (%)	Salinity S (mg/m^2-d)	Categorized Values
$P \le 10$	<70	$S \le 3$	0
$10 < P \le 12$	≥70	$3 < S \le 40$	1
$12 < P \le 35$	Do not	$40 < S \le 60$	2
$35 < P \le 80$	Transform	$60 < S \le 300$	3
$80 < P \le 700$	—	$300 < S \le 5{,}000$	4

TABLE 3
Categorized Values According to Table 2

Exposure Site	SO_2 (mg/m^2-d)	Salinity (mg/m^2-d)	RH (%)
Aligarh	1	1	1
Bhavnagar	—	—	1
Bhopal	—	1	1
Bhubaneswar	0	1	1
Chandigarh	0	1	1
Naval base Chennai	2	4	1
Coimbatore	0	1	1
Cuddalore	0	3	1
Dindigul	0	1	0
Hyderabad	—	1	0
Jorhat	0	1	1
CECRI Unit Kochi	2	2	1
Kakinada	0	3	1
Karaikudi	0	1	1
Kolkota	2	1	1
Kanyakumari	0	1	1
kayamkulam	2	4	1
Lucknow	—	1	1
Mahendragiri	0	0	1
Manali	2	3	1
Mandapam Camp	0	3	0
Mangalore	Traces	3	1
Marumagao	2	4	1
Mettupalayam	4	Traces	1
Mumbai	2	2	1
Nagapattinam	0	1	1
Naval Base Kochi	2	3	1
New Delhi	—	—	1
NIO Goa	0	0	1
Padubidri	0	3	1
Pondicherry	1	1	1
Port Blair	0	4	1
Pune	1	1	1
Salem	0	2	1
Sriharikota	0	4	1
Surat	0	1	1
Tirupur	0	1	1
Tuticorin	4	2	1
Visakhapatnam	2	1	1
Warangal	—	—	1

Atmospheric corrosion steel in the Canadian arctic and subarctic regions were performed by Biefer.[13] Singh, et al.,[14] prepared a map to show the geographical positions of the atmospheric corrosion test sites. They collected rust samples of mild steel panels exposed at eight different sites in Sweden. The corrosion rate was high with increasing SO_2 concentration. Lipfert[15] studied the effect of acidic deposition on the atmospheric degradation of constructing materials, such a zinc, copper, and aluminum, due to the action of natural weathering and atmospheric pollutants. Mansfeld and Kumar[16] used tables and line graphs to represent the results of atmospheric corrosion in Southern and Northern California using galvanized steel. Lloyd and Manning[17] used the map to show the location details as well as total sodium deposition rate in that site using steel as the specimen. This study detailed the change in the corrosion rate due to the inland transport of sea salt. Porro, et al.,[18] generated a formula to estimate the corrosion rate of carbon steel from SO_2 and chloride levels. The increase of the corrosion rate in a marine environment as a result of relative humidity, chlorides, sulfur dioxide, and pollution was discussed by Julve and Gustems.[19] Location details of the corrosion test sites in the Caribbean area was produced in the form of a map by Corvo, et al.[20] Atmospheric corrosion rates at six sites in Argentina were studied by Vilche, et al.,[21] using metrological and pollution parameters and from the weight-loss data on copper samples. Veleva and Maldonado[22] prepared a map to show the test sites located in the Yucatan peninsula. Chung, et al.,[23] mapped the geographical location/distribution of 23 test sites for a galvanized steel exposure program in Taiwan.

Using 14 test sites in the tropical humid atmosphere of the Yucatan peninsula and the Mexican Caribbean area, the corrosion rate of flat plate samples of copper, carbon steel, and zinc were determined by Maldonado and Veleva.[24] Rincón, et al.,[25] measured the atmospheric pollutant level and their influence on metals or alloys. Ahmed, et al.,[26] studied the most corrosive environment, Dhahran, located on the eastern coast of Saudi Arabia. Corrosion of the weathering steel and carbon steels in Japan was studied by Asami and Kikuchi.[27] The behavior of nickel panel, exposed to industrial, urban, and rural environments in the region of France, was found by Jouen, et al.[28]

It has been nearly 38 years since the first corrosion map of India was made.[29] Since that time, many environmental changes have occurred because of industrialization, population growth, and an enormous growth in vehicle population. Central Electrochemical Research Institute (CECRI, Karaikudi, India) has initiated a long awaited exercise to prepare a new corrosion map of India. The authors[30-34] prepared an updated corrosion map of India relating to four metals: carbon steel, zinc, galvanized steel, and aluminum. The map was prepared based on the data collected from 41 testing sites. These data indicate that corrosiveness is area-specific and not region-specific. The maps of the atmospheric corrosion rate of structural metals were performed by de Rincón and coworkers.[35-36] The pie diameter corresponds to mass corrosion loss and not the corrosiveness classification interval as defined in ISO 9223. A new approach for reporting the characterization of an atmosphere

TABLE 4
Transformed Values from 0 to 4

Exposure Site	Temperature (°C)	Relative Humidity (%)	Rainfall (mm/y)	SO_2 (mg/m²-d)	Salinity (mg/m²-d)	Σ Values
Aligarh	0	1.12	0.259	0.069	0.016	1.464
Bhavnagar	2.86	0.96	0.218	—	—	4.038
Bhopal	1.14	0.96	0.637	—	0.019	2.756
Bhubaneswar	2.28	1.04	0.417	0.050	0.017	3.804
Chandigarh	0	1.2	0.328	0	0.014	1.542
Naval base Chennai	3.71	1.04	0.443	0.114	1.389	6.696
Coimbatore	4	1.44	0.290	0.0006	0.016	5.747
Cuddalore	2.86	1.6	0.904	0	0.050	5.414
Dindigul	3.42	0	0.055	0.05	0.001	3.526
Hyderabad	3.71	0.64	0.19	—	0.014	4.554
Jorhat	1.42	1.36	0.883	0.063	0.017	3.744
CECRI Unit Kochi	2.28	0.88	0.742	0.196	0.040	4.14
Kakinada	2.57	1.36	0.396	0	0.097	4.423
Karaikudi	2.28	0.88	0.210	0	0.030	3.400
Kolkota	0.57	0.8	0.396	0.120	0.021	1.907
Kanyakumari	2.86	0.88	0.089	0	0.030	3.859
Kayamkulam	0.57	3.84	0.587	0.114	0.358	5.419
Lucknow	2	1.76	0.117	—	0.0224	3.899
Mahendragiri	2.86	3.92	0.081	0	0	6.861
Manali	3.42	1.84	0.381	0.158	0.096	5.419
Mandapam Camp	3.71	0.08	0.098	0	0.197	4.085
Mangalore	2	1.68	0.380	Traces	0.088	4.148
Marumagao	1.14	1.04	0.3	0.139	0.340	2.959
Mettupalayam	2.57	3.6	0	4	Traces	10.170
Mumbai	1.71	1.04	1.228	0.088	0.0384	4.104
Nagapattinam	2.86	0.56	0.968	0	0.0232	4.411
Naval Base Kochi	2.57	1.52	0.758	0.196	0.0632	5.107
New Delhi	0	1.6	0.215	—	—	1.815
NIO Goa	0.28	1.44	0.3	0	0	2.020
Padubidri	1.42	1.92	0.383	0.057	0.099	3.879
Pondicherry	3.14	0.88	0.948	0.069	0.030	5.067
Port Blair	2	1.84	4	0	0.285	8.125
Pune	1.14	1.28	0.192	0.076	0.027	2.715
Salem	4	0.88	0.061	0	0.036	4.977
Sriharikota	2.57	1.12	0.568	0	4	8.259
Surat	2.86	0.96	0.383	0.05	0.018	4.271
Tirupur	3.14	4	0.255	0.006	0.016	7.417
Tuticorin	2.86	1.12	0.09	3.390	0.047	7.507
Visakhapatnam	2.86	1.76	0.405	0.082	0.018	5.125
Warangal	4	0.88	0.196	—	—	5.076

in a single map is proposed for four metals, allowing corrosion rate, pollution levels, and climatic parameters that mainly affect each particular microclimate to be shown. The Indian updated atmospheric corrosiveness maps are presented with this new outlook. These maps have been developed using one-year data collected from 41 field exposure sites in India.[30] Statistical analyses are represented with pie charts with diameters varying according to the corrosion rate. The idea of creating pies for the parameters according to the corrosion rate has been taken from the material published by de Rincón, et al.[35]

EXPERIMENTAL PROCEDURES

Scope and methodology of conducting the atmospheric corrosion studies were similar for all 41 exposure sites. The climatic parameters, which influence atmospheric corrosion, are salinity, sulfur dioxide (SO_2), relative humidity (RH), temperature, and other pollutants. The atmospheric test sites were chosen according to the local atmosphere, convenience of installation, and availability of technical assistance. Locations of these atmospheric test sites are given in Table 1. Carbon steel (CS), zinc (Zn), galvanized steel (GS), and aluminum (Al) were used for the field exposure studies at each test location. The general guidelines from the Indian Standard,[37] ASTM International,[38-40] and the International Organization for Standardization (ISO)[41] were used for the exposure and cleaning procedures required before exposure and for cleaning and evaluation after the exposure. The average climatic parameters such as temperature, RH, and rainfall have been collected from meteorologi-

TABLE 5
Transformed Values of the Variables Under Study on Scale from 0 to 360°

Exposure Site	Temperature (°C)	Relative Humidity (%)	Rainfall (mm/y)	SO_2 (mg/m²-d)	Salinity (mg/m²-d)
Aligarh	0	275.4	63.680	16.960	3.934
Bhavnagar	254.97	85.58	19.430	—	—
Bhopal	148.90	125.39	83.200	—	2.507
Bhubaneswar	215	98.42	39.460	4.732	1.589
Chandigarh	0	280.08	76.550	0	1.360
Naval base Chennai	234.48	65.73	27.990	7.205	24.570
Coimbatore	250.58	90.20	18.167	0.037	1.002
Cuddalore	190.15	106.38	60.106	0	3.351
Dindigul	349.15	0	5.615	5.104	0.123
Hyderabad	293.25	50.58	15.010	—	1.138
Jorhat	136.55	130.78	84.910	6.058	1.692
CECRI Unit Kochi	198.35	76.55	64.550	17.050	3.479
Kakinada	209.18	110.69	32.230	0	3.213
Karaikudi	241.38	93.16	22.230	0	3.218
Kolkota	107.61	151.03	74.760	22.650	3.926
Kanyakumari	266.77	82.08	8.301	0	2.835
Kayamkulam	37.86	255.08	38.090	7.572	23.80
Lucknow	184.04	162.48	10.800	—	2.068
Mahendragiri	150.06	205.68	4.250	0	0
Manali	208.85	112.36	23.260	9.648	5.86
Mandapam Camp	26.96	7.050	8.636	0	17.34
Mangalore	173.57	145.8	32.970	—	7.630
Marumagao	138.69	126.52	36.490	16.900	41.360
Mettupalayam	90.97	127.43	0	141.590	—
Mumbai	149.98	91.21	107.700	7.718	3.368
Nagapattinam	233.40	45.7	78.990	0	1.893
Naval Base Kochi	181.15	107.14	53.430	13.81	4.454
New Delhi	0	317.35	42.640	—	—
NIO Gao	59.9	256.63	53.450	0	0
Padubidri	131.77	178.10	36.370	5.280	9.20
Pondicherry	223.10	62.52	67.350	4.900	2.103
Port Blair	88.61	81.52	177.230	0	12.619
Pune	151.14	169.96	25.450	10.070	3.606
Salem	289.30	63.65	4.412	0	2.606
Sriharikota	112.02	48.81	24.800	0	174.350
Surat	241.09	80.92	32.280	4.214	1.483
Tirupur	152.40	194.14	12.370	0.290	0.776
Tuticorin	137.14	53.708	4.315	162.560	2.260
Visakhapatnam	200.88	123.61	28.440	5.759	1.292
Warangal	283.68	62.41	13.900	0	0

cal observatory stations of the Government of India. Pollution as a result of SO_2 [P] and airborne salinity [S] were evaluated continuously every month for one year by the deposition methods (by lead peroxide [PbO_2] candle and wet candle methods, respectively).[39] SO_2 of the atmosphere absorbed by the lead peroxide was transformed into lead sulfate ($PbSO_4$), which was then analyzed using the gravimetric method. The amount of chloride captured by the wet candle method was determined using the titration method. The metal specimens were mounted on the exposure racks at an angle of 45° from the horizontal. To identify the exposed specimens, stamped code numbers were used. The exposure racks were located in open atmosphere carefully avoiding the shadows of trees, buildings, or structures. Details of the chemical compositions, size of the metal panels, SO_2 [P] and airborne salinity [S], climatic parameters, and the yearly corrosion rates of the four metals of each site are provided in an earlier publication.[30] Using all of these parameters, the sectors of the pie charts were drawn. A new map has been produced to show the parameters of the sites in the form of pie charts; the diameter of the pie is drawn on the basis of the corrosion rate.

RESULTS AND DISCUSSION

Table 1 shows the yearly average climatic parameter values of the various sites. The pollutants' variable SO_2 and salinity were categorized as P and S, respectively, by the ISO standard.[42] Further, it was assumed that RH values <70% did not affect the corrosion rate. It is applicable only to rural and urban

TABLE 6
Diameter of the Pie Chart According to the Corrosion Rate of Carbon Steel

Exposure Site	Corrosion Rate (μm/y)	Diameter (cm)
Aligarh	15.904	1.510
Bhavnagar	12.730	1.505
Bhopal	9.820	1.500
Bhubaneswar	24.400	1.523
Chandigarh	21.440	1.518
Naval base Chennai	524.000	2.308
Coimbatore	16.000	1.510
Cuddalore	51.300	1.565
Dindigul	69.720	1.511
Hyderabad	23.511	1.522
Jorhat	7.439	1.496
CECRI Unit Kochi	90.500	1.627
Kakinada	82.000	1.614
Karaikudi	19.970	1.516
Kolkota	22.600	1.520
Kanyakumari	15.640	1.509
Kayamkulam	42.000	1.551
Lucknow	12.320	1.504
Mahendragiri	13.570	1.506
Manali	115.000	1.665
Mandapam Camp	109.050	1.656
Mangalore	108.400	1.655
Marumagao	453.900	2.198
Mettupalayam	300.000	1.956
Mumbai	44.000	1.554
Nagapattinam	28.900	1.530
Naval Base Kochi	156.600	1.731
New Delhi	19.770	1.516
NIO Goa	30.00	1.532
Padubidri	43.000	1.552
Pondicherry	27.420	1.528
Port Blair	380.000	2.082
Pune	12.400	1.504
Salem	16.160	1.510
Sriharikota	1,600.000	4.000
Surat	27.300	1.528
Tirupur	18.000	1.513
Tuticorin	83.810	1.616
Visakhapatnam	36.690	1.542
Warangal	9.843	1.500

TABLE 7
Diameter of the Pie Chart According to the Corrosion Rate of Galvanized Steel

Exposure Site	Corrosion Rate (μm/y)	Diameter (cm)
Aligarh	2.779	1.525
Bhavnagar	0.402	1.503
Bhopal	0.117	1.500
Bhubaneswar	1.492	1.513
Chandigarh	1.616	1.514
Naval base Chennai	11.660	1.607
Coimbatore	—	—
Cuddalore	4.200	1.538
Dindigul	2.084	1.518
Hyderabad	2.360	1.521
Jorhat	1.047	1.509
CECRI Unit Kochi	2.860	1.525
Kakinada	—	—
Karaikudi	0.381	1.503
Kolkota	1.754	1.515
Kanyakumari	2.489	1.522
Kayamkulam	—	—
Lucknow	7.344	1.567
Mahendragiri	3.520	1.532
Manali	4.560	1.541
Mandapam Camp	12.550	1.615
Mangalore	6.710	1.561
Marumagao	184.100	3.204
Mettupalayam	—	—
Mumbai	3.600	1.532
Nagapattinam	0.322	1.502
Naval Base Kochi	6.445	1.559
New Delhi	2.845	1.525
NIO Goa	2.260	1.520
Padubidri	—	—
Pondicherry	—	—
Port Blair	270.000	4.000
Pune	2.420	1.521
Salem	1.400	1.512
Sriharikota	—	—
Surat	2.540	1.523
Tirupur	—	—
Tuticorin	24.480	1.726
Visakhapatnam	2.750	1.524
Warangal	6.500	1.559

atmospheres having lesser pollutant levels. But, in the case of marine sites such as the Naval Base Chennai, Kayamkulam, Marumagao, and Port Blair, the layer of deposited sodium chloride (NaCl) is highly hygroscopic and absorbs air humidity even in a 20% RH environment. A procedure was applied to these values, leading to the new approach of atmospheric corrosiveness maps made with pies instead of isolines or colors. Conventional techniques may not be adequate for reporting results when there are a relatively small number of sites.

Table 2 shows the criteria that had been used for categorizing the variables into four. After categorizing these variables, the remaining climatic variables such as temperature, rainfall, and RH were also categorized. Table 3 shows the results of the categorized values of the variable sites. After categorizing these variables, they were transformed to the scale from 0 to 4. Table 4 presents the values transformed to this scale by using the equation:

$$Vt = 4(V - Vmin)/(Vmax - Vmin) \quad (1)$$

where 4 is the maximum categorization constant, Vt is the transformed value of the variable station, V is the untransformed value (Table 1), Vmax is the maximum value of the variable site (Table 1), and Vmin is the minimum value of the variable station.

The pies then were drawn with the contribution of each particular variable in the circumference area being determined in accordance with the following equation:

$$Vt^* = (360\ Vt)/\Sigma \text{ values} \quad (2)$$

TABLE 8
Diameter of the Pie Chart According to the Corrosion Rate of Zinc

Exposure Site	Corrosion Rate (μm/y)	Diameter (cm)
Aligarh	2.263	1.604
Bhavnagar	0.385	1.502
Bhopal	0.356	1.500
Bhubaneswar	0.828	1.526
Chandigarh	1.200	1.546
Naval base Chennai	7.100	1.869
Coimbatore	1.000	1.535
Cuddalore	2.200	1.600
Dindigul	4.958	1.752
Hyderabad	2.556	1.621
Jorhat	0.881	1.529
CECRI Unit Kochi	2.530	1.619
Kakinada	—	—
Karaikudi	1.100	1.540
Kolkota	1.290	1.551
Kanyakumari	1.960	1.588
Kayamkulam	3.000	1.645
Lucknow	5.067	1.758
Mahendragiri	6.250	1.823
Manali	23.800	2.784
Mandapam Camp	12.150	2.146
Mangalore	1.370	1.555
Marumagao	19.412	2.544
Mettupalayam	7.000	1.864
Mumbai	2.600	1.623
Nagapattinam	2.700	1.628
Naval Base Kochi	6.304	1.826
New Delhi	0.560	1.511
NIO Goa	1.260	1.550
Padubidri	2.000	1.590
Pondicherry	0.992	1.535
Port Blair	220.000	13.530
Pune	1.480	1.561
Salem	1.655	1.571
Sriharikota	46.000	4.000
Surat	2.080	1.594
Tirupur	0.100	1.486
Tuticorin	32.200	3.244
Visakhapatnam	3.600	1.678
Warangal	2.805	1.634

TABLE 9
Diameter of the Pie Chart According to the Corrosion Rate of Aluminum

Exposure Site	Corrosion Rate (μm/y)	Diameter (cm)
Aligarh	0.538	1.527
Bhavnagar	0.185	1.497
Bhopal	0.230	1.500
Bhubaneswar	0.731	1.544
Chandigarh	0.138	1.493
Naval base Chennai	8.600	2.228
Coimbatore	4.000	1.828
Cuddalore	1.162	1.582
Dindigul	<0.100	1.481
Hyderabad	0.434	1.518
Jorhat	<0.100	1.485
CECRI Unit Kochi	0.180	1.496
Kakinada	—	—
Karaikudi	0.395	1.515
Kolkota	0.231	1.500
Kanyakumari	3.12	1.751
Kayamkulam	0.500	1.524
Lucknow	7.28	2.113
Mahendragiri	5.320	1.943
Manali	1.410	1.603
Mandapam Camp	0.700	1.541
Mangalore	5.100	1.924
Marumagao	11.000	2.436
Mettupalayam	9.000	2.263
Mumbai	2.500	1.698
Nagapattinam	<0.100	1.482
Naval Base Kochi	0.87	1.556
New Delhi	0.295	1.506
NIO Goa	0.248	1.502
Padubidri	1.400	1.602
Pondicherry	0.100	1.489
Port Blair	40.000	4.956
Pune	<0.100	1.483
Salem	<0.100	1.482
Sriharikota	<0.100	4.000
Surat	3.930	1.822
Tirupur	3.000	1.741
Tuticorin	27.100	3.835
Visakhapatnam	4.850	1.902
Warangal	<0.100	1.486

where Vt* is the transformed values of the variable station on a scale from 0 to 360 degrees, Vt is the transformed values of the variable station on a scale from 0 to 4, and Σ values is the sum of all the variables in a station. The transformed values of the climatic and pollutant variable on a scale from 0 to 360° obtained from Equation (2) are given in Table 5.

The diameter of the pie provided information on the atmospheric corrosiveness. A minimum and maximum diameter of 1.5 and 4 were used. The diameter of the pie was calculated as follows:

$$d = 2.5(CR - CRmin)/(CRmax - CRmin) + 1.5 \quad (3)$$

where d is the diameter of the pie, CR is the corrosion rate, CRmin is the minimum corrosion rate of that metal, and CRmax is the maximum corrosion rate of that metal. The corrosion rate and diameter of the pie chart with respect to carbon steel, galvanized steel, zinc, and aluminum are given in Tables 6 through 9, respectively.

The diameter of the pie corresponds to the corrosion rate of that particular metal in that site (Figures 1 through 4). These figures present the maps prepared with the above-mentioned indications, including the corrosiveness category that considers atmospheric characteristics. As soon as the diameter was calculated, the pies were drawn and they were shown in the maps. The process was repeated for all four metals. Four maps show the pie diagram of the parameters that had been used to calculate the corrosion rate. The circumference of the pie corresponds to that of the corrosion rate of the metal in that variable station. Making the maps using pies has a clear

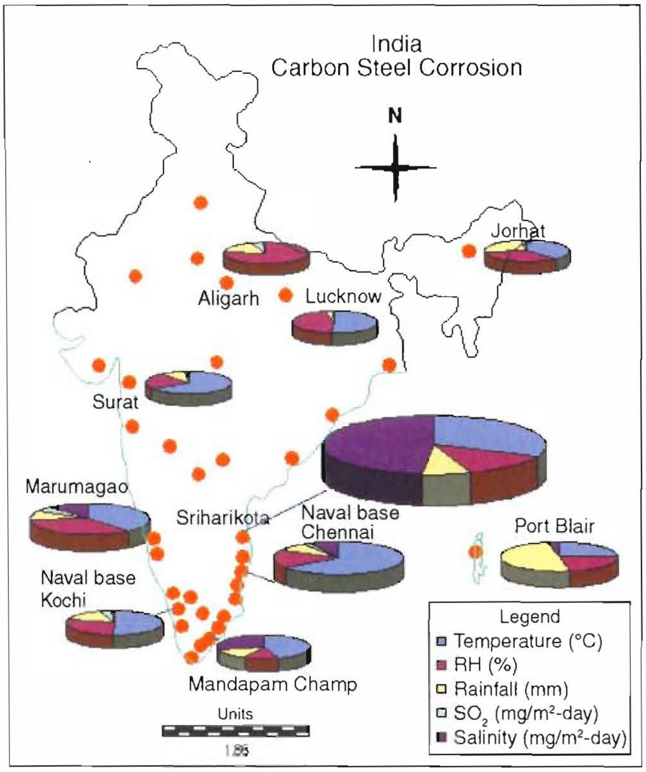

FIGURE 1. *Updated map of atmospheric corrosiveness for carbon steel (based on pie diagram of the parameters).*

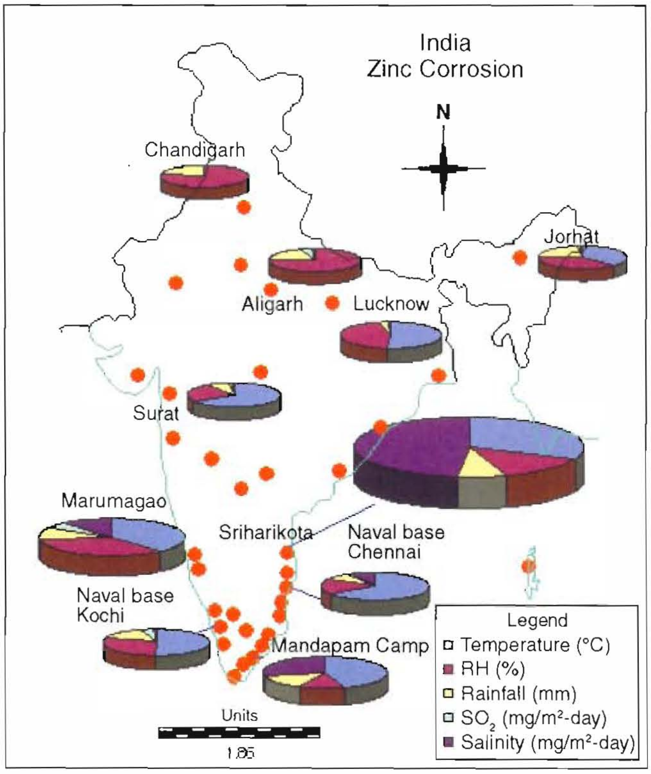

FIGURE 2. *Updated map of atmospheric corrosiveness for zinc (based on pie diagram of the parameters).*

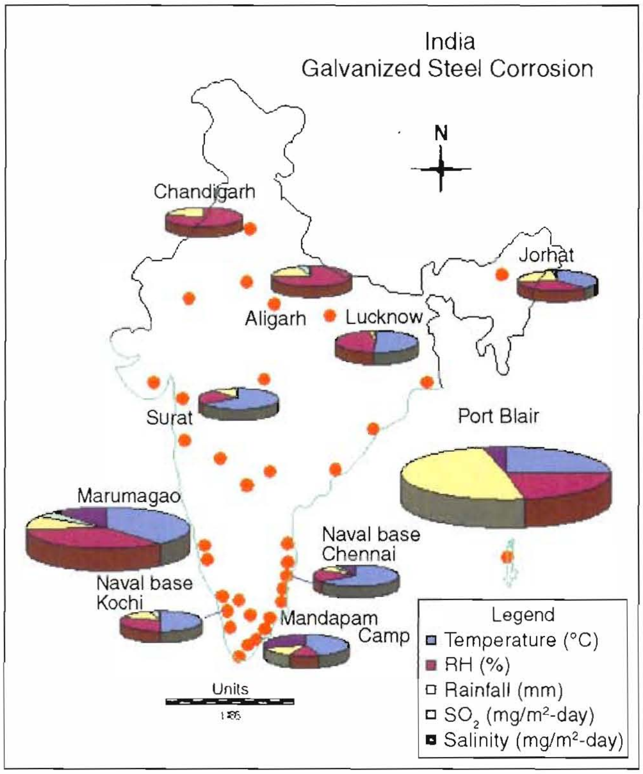

FIGURE 3. *Updated map of atmospheric corrosiveness for galvanized steel (based on pie diagram of the parameters).*

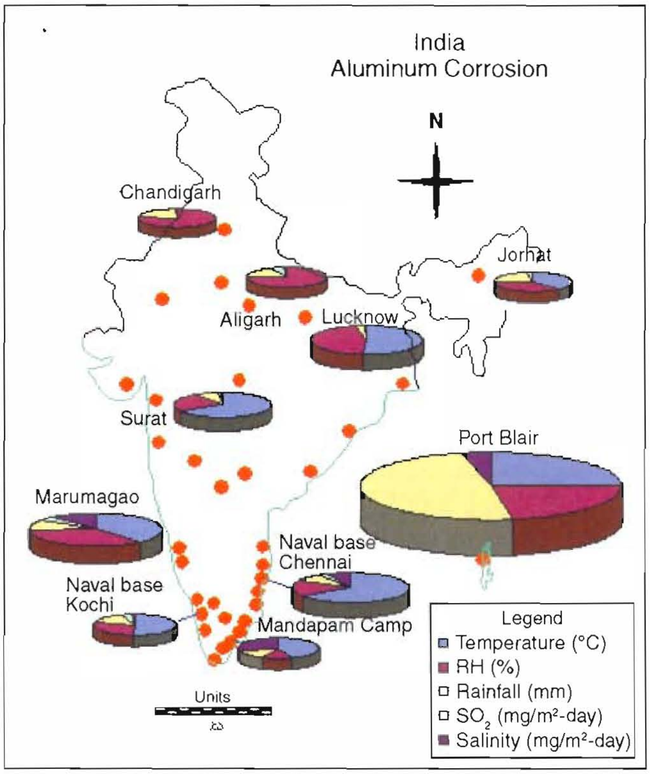

FIGURE 4. *Updated map of atmospheric corrosiveness for aluminum (based on pie diagram of the parameters).*

advantage. In addition to giving an adequate representation of the results, the effect of microclimates can be seen easily, as well as the differences in the corrosiveness of each particular atmosphere. These maps quickly show that the area with the lowest corrosion rate of carbon steel is at Jorhat and the highest is at Sriharikota. According to the analyses carried out, all variables affecting the process needs to be evaluated when considering the aggressiveness of an atmosphere.

CONCLUSIONS

❖ Using the same set of data collected, a new set of formulas was applied to calculate the diameter of the pie charts. The maps of the atmospheric corrosion rate of structural metals were produced using pies representing the atmospheric quality of each particular climate. The pie diameter corresponds to mass corrosion loss and not the corrosiveness classification interval as defined in ISO 9223. The climate was to be correctly characterized using the pies. The pies were drawn only for a limited number of variable stations, and this was the only limitation when the pies were drawn. Four different maps were drawn in the same manner. The climatic parameters were used to represent the wedge of the pie. According to the corrosion rate of that particular variable station, the diameter of the pie was fixed. Based on the results obtained, the corrosion rate for the Sriharikota and Port Blair sites were found to be high, and low at the Jorhat site.

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