
A NOVEL APPROACH TO THE MATHEMATICAL MODELLING OF ATMOSPHERIC CORROSION RATES FROM FRAGMENTED SUBTROPICAL ENVIRONMENTS

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Abstract

A new mathematical model for the estimation of atmospheric corrosion rates that satisfactorily describes the behaviour of carbon steel in a fragmented subtropical region has been developed. It is a semi-empirical equation that includes a set of qualitative coefficients established from collections at short exposures (typically one year), in addition to environmental parameters, namely duration of exposure, time of wetness, and deposition rate for chloride ions and sulphur dioxide. The validity of the proposed model has been tested by comparing the estimates obtained using this equation with the experimental data collected from 35 outdoor test sites during 3 years. Satisfactory estimates of the corrosion rates matching the majority of the experimental observations for longer exposures were obtained.

Keywords: atmospheric corrosion, mathematical models, carbon steel, fragmented geographical area, subtropical region

1. Introduction

Corrosion of metals exposed to the atmosphere is an important issue due to the high costs paid by industries due to shorter service lives of structures and components. Accordingly, the establishment of corrosivity categories became the main goal in the field of atmospheric corrosion during the 20th century [1]. Nowadays, environments are usually classified in terms of corrosivity indexes

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according to the ISO 9223 standard [ISO 9223:1992(E), *Corrosion of metals and alloys – Corrosivity of atmospheres – Classification*, Geneva, 1992]. Alternate classification procedures have also been proposed, including the *PACER LIME algorithm* developed by the *Maintenance Management of Structural Aircraft Systems* [2]. Environments are classified according to four categories, namely very severe (AA), severe (A), moderate (B), and mild (C). The parameters employed in the evaluations procedure include the distance to the sea, SO₂ and ozone concentrations, time of wetness, and the total amount of particles suspended in the air. The maximum category AA is assigned to locations up to 4.5 km from the coastline, which is the most frequent situation encountered in fragmented archipelagic territories, as it is the case of the Canary Islands belonging to Spain.

Numerous research programmes have been undertaken for the characterization of atmospheric corrosivity distributions in a variety of geographical regions [3-10], in the aim to derive mathematical models for the prediction of the corrosion rates for different metals in extended geographical zones. Nevertheless, the high complexity and non-linearity of the physicochemical processes involved in atmospheric corrosion greatly difficult the prediction of corrosion rates [11]. Yet various models have been proposed until now, some of them covering large geographical regions as it was the case with the *ISO CORRAG* [12], and with *The International Cooperative Program on Effects, The Iberoamerican Atmospheric Corrosion Map Project MICAT (Mapa Iberoamericano de Corrosión Atmosférica)* [13]. Models proposed in the literature are regression procedures that use the partial least-squares method to fit sets of experimental data to mathematical equations, but their applicability is often restricted to rather small territories, and they usually fail when extrapolation to other localities, or to areas presenting significant non-linearities, was attempted. In fact, those models have failed to describe the atmospheres of subtropical regions [4, 14], where the ISO 9223 has limited applicability [6].

Our research group has worked on the elaboration of a Corrosion Map for the Canary Islands. The aggressiveness of the environments distributed in the province of Santa Cruz de Tenerife was evaluated from the effects experienced of various metallic materials, namely carbon steel, galvanized steel, copper, zinc and aluminium, in outdoor exposures. Regarding carbon steel, corrosivity categories were then assigned on the basis of weight loss measurements for samples retrieved from 35 test sites after 1 year exposure [15]. It was found that 64.7% of the locations corresponded to the category C2, 26.5% to C3, and the remaining 8.8% to C5. Corrosivity categories C1 and C4 were not assigned to any location.

In this work we report on various modelling procedures designed to predict the corrosion rates experienced by carbon steel in a fragmented subtropical territory. The availability of corrosion rates for this material, and the corresponding environmental parameters, during a period of 3 years allowed the validity of those models to be tested. Different combinations of the environmental parameters were taken in consideration. Additionally, an

evaluation was made of the impact produced by the inclusion of a set of qualitative coefficients that would distinguish the test sites exhibiting different corrosivity degrees at early exposures. The mathematical models allowed evaluation of the specific impact of the different environmental parameters, namely time of wetness, duration of exposure, and deposition rates of pollutants (e.g., chloride ions and sulphur dioxide). The models were discussed in terms of their corresponding fit quality.

2. Experimental

Carbon steel plates of dimensions 100x40x20 mm³ were used. The composition of the carbon steel is given in Table 1. Prior to exposure, carbon steel plates were cleaned according to the ASTM G1-90 norm [16], and subsequently weighed using a Sartorius BP210S balance. Samples were collected after 3, 6, 9, 12, 18, 24, and 36 month exposures. Corrosion products were removed by chemical operation as described by the ISO/DIS 8403.3 [ISO/DIS 8403.3, *Metals and alloys. Procedures for removal of corrosion products from corrosion test specimens*, Geneva, 1985]. After the samples were cleaned and dried, they were weighed again. Corrosion rates were determined from weight loss measurements.

Table 1. Chemical composition of the carbon steel.

Sample	Elements (%)					
	Si	Fe	C	Mn	P	S
Carbon steel	0.080	99.467	0.060	0.370	0.009	0.014

A detailed description of both the location of the test sites and the characteristics of the pollutant collectors and the meteorological sensors can be found in a previous work [6]. In brief, the Canary Islands constitute an archipelago located in the Atlantic Ocean, between latitudes 27°38' and 29°25' North and longitudes 13°30' and 18°19' West, making up a total surface of 7,499 km² (see Figure 1). The 35 test sites were distributed in the four western islands that constitute the province of Santa Cruz de Tenerife. The climate is characterised by the combined action of the cold oceanic Canary Stream and the Trade Winds blowing in Northeast direction. The rough relieve of the islands induces the stagnation of clouds which are swept by the Trade Winds originating a very humid environment. The measurement of SO₂ pollution was performed using ISO/TC 156 N 250 norm (i.e., Husy method) [ISO/TC 156 N 250, *Corrosion of metal and alloys. Aggresivity of atmospheres. Methods of measurement of pollution data*, Geneva, 1986], whereas ISO/DP 9225 norm [ISO/DP 9225, *Corrosion of metals and alloys. Corrosivity of atmospheres. Methods of measurement of pollution*, Geneva, 1992] was employed for chlorides. Time of wetness (*TOW*) was established from relative humidity (*RH*) and temperature data. They were evaluated as those lengths of time characterized by $RH \geq 80\%$ and temperatures $\geq 0^\circ\text{C}$. Finally, data on the speed

and direction of wind were kindly supplied by the National Meteorological Institute of Spain (AEMET).

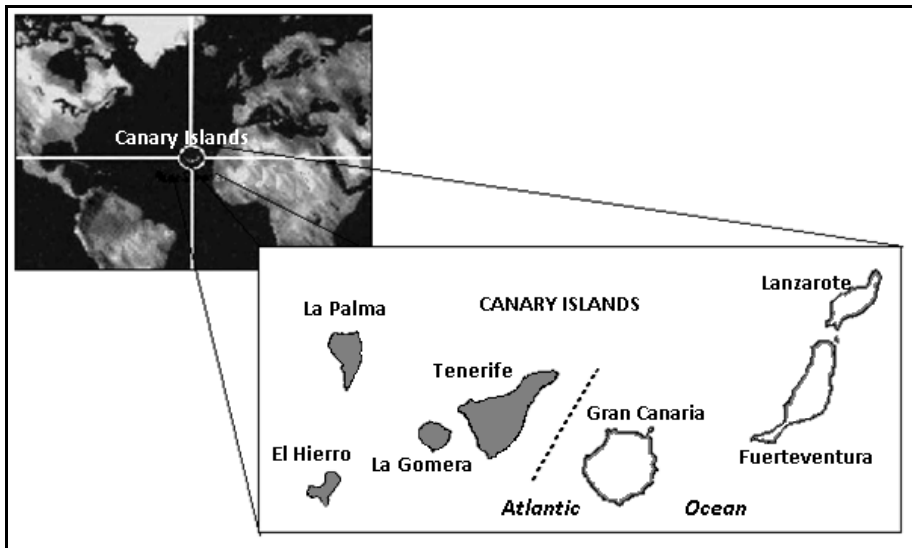


Figure 1. Geographical location of the Canary Islands (Spain).

3. Mathematical modelling

The models evaluated in this work can be classified in two classes at first. One class is characterized by containing the duration of exposure (*TEXP*, in years) as only experimental parameter for the prediction of the corrosion rates (*CR*, $\mu\text{m year}^{-1}$), while containing some qualitative coefficients introduced for fitting purpose. The following four mathematical equations resulted:

$$\ln(CR) = k_0 + k_1 \text{TEXP} \quad (1)$$

$$\ln(CR) = k_0 + k_1 \text{TEXP} + \delta_2 D2 + \delta_3 D3 + \delta_4 D4 \quad (2)$$

$$\ln(CR) = k_0 + k_1 \ln(\text{TEXP}) \quad (3)$$

$$\ln(CR) = k_0 + k_1 \ln(\text{TEXP}) + \delta_2 D2 + \delta_3 D3 + \delta_4 D4 \quad (4)$$

The second class corresponds to equations containing the environmental parameters and the interactions between them, in addition to the use of qualitative coefficients analogously to the previous case. Those environmental parameters are namely, time of wetness (*TOW*, year), chloride ion concentration (*CL*, $\text{g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$), and concentration of SO_2 (*SO2*, $\text{g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$). The corresponding equations are given by:

$$\ln(CR) = k_0 + k_1(\text{SO2}) + k_2(\text{CL}) + k_3 \ln(\text{TOW}) + k_4(\text{SO2})(\text{CL}) + k_5 \ln(\text{TEXP}) + k_6(\text{SO2})\ln(\text{TEXP}) + k_7(\text{CL})\ln(\text{TEXP}) + k_8(\text{SO2})(\text{CL})\ln(\text{TEXP}) + k_9(\text{TOW})\ln(\text{TEXP}) \quad (5)$$

$$\ln(CR) = k_0 + k_1(\text{SO2}) + k_2(\text{CL}) + k_3 \ln(\text{TOW}) + k_4(\text{SO2})(\text{CL}) + k_5 \ln(\text{TEXP}) + k_6(\text{SO2})\ln(\text{TEXP}) + k_7(\text{CL})\ln(\text{TEXP}) + k_8(\text{SO2})(\text{CL})\ln(\text{TEXP}) + k_9(\text{TOW})\ln(\text{TEXP}) + \delta_2 D2 + \delta_3 D3 + \delta_4 D4 \quad (6)$$

$$\ln(CR) = k_0 + k_1 \ln(SO_2) + k_2 \ln(CL) + k_3 CL + k_4 \ln(TOW) + k_5 (SO_2) \ln(TEXP) \quad (7)$$

$$\ln(CR) = k_0 + k_1 \ln(SO_2) + k_2 \ln(CL) + k_3 CL + k_4 \ln(TOW) + k_5 (SO_2) \ln(TEXP) + \delta_2 D_2 + \delta_3 D_3 + \delta_4 D_4 \quad (8)$$

In order to assist fitting, test sites were grouped according to their corrosivity categories. Thus, grouping *G1* includes the sites with corrosivity category *C2*; grouping *G2* those of category *C3*; and grouping *G3* those of category *C5*. No test sites were found to correspond to corrosivity categories *C1* and *C4*. Table 2 lists the test sites together with their corrosivity categories and the assigned groupings, as well as the corrosion rates determined after 12, 18, 24 and 32 month exposures.

Values were assigned to the qualitative coefficients to describe the four groupings. They were defined as follows: $D_1 = 1$, for an observation corresponding to a test site belonging to the first grouping (*G1*), otherwise $D_1 = 0$; $D_2 = 1$ for one corresponding to grouping *G2*, otherwise $D_2 = 0$; $D_3 = 1$ in the case of grouping *G3*, and $D_3 = 0$ for the others; and, $D_4 = 1$ in the case of *G4*, while $D_4 = 0$ in any other situation.

4. Results and discussion

The orography of the islands comprised in the province Santa Cruz de Tenerife favours the development of a wide variety of microclimates in a small geographical area. These microclimates influence the corrosion of carbon steel in different degrees.

Among the islands, Tenerife is unique by displaying 6 differentiated microclimates along a very abrupt orography, including the highest mountain in Spain and in any island in the Atlantic Ocean (Mount Teide is 3,718 meters above sea level). This is the reason for the distribution of environments along its territory. The most aggressive environments are found at the South of the island, characterized by predominant Eastern winds with maximum speeds up to $30 \text{ km}\cdot\text{h}^{-1}$ (see Figure 2). The mildest environments can be found at the North and the East of the island, the latter being an urban zone. On the basis of these findings, the development of a single mathematical model able to describe such wide variety of environments was a rather complicated task.

Based on the acceptance of the model proposed by Legault and Pearson [15], two equations correlating the corrosion rate with the exposure time were first tested. They contained either a semi-logarithmic (Equation (1)) or a double-logarithmic (Equation (3)) functions. Correlation ratios were very low in both cases (0.2433 for Equation (1), and 0.2422 for Equation (3)). Additionally, it can be noticed that the generated parameter k_7 became negative and smaller than 0.5, as shown in Table 3.

In principle, these results are consistent with the big diversity of environments distributed among the test sites under consideration. The data come from a total of 236 collections performed along three years, which show a wide variation in the corrosion rates (cf. Table 2). Although the parameter k_7

(equivalent to exponent n in the double-logarithmic law) attained a small value, that would rather correspond to conditions of moderate atmospheric aggressiveness, this can be further developed by introducing the influence of the environmental parameters into the Model.

Table 2. Corrosivity categories established from weight loss measurements, assigned grouping, and values of the qualitative variables for each corrosion site.

Site	Location	G	D	Corrosion rate ($\mu\text{m year}^{-1}$)				Corrosion category
				Duration of exposure (month)				
				12	18	24	36	
1	Meteorológico	1	1	14.12	9.58	9.58	7.04	C2
2	Policía S/C Tenerife	1	1	17.45	11.32	11.32	8.64	C2
3	Oceanográfico	1	1	16.73	12.96	12.96	11.75	C2
4	Ofra	1	1	26.83	14.96	14.96	12.96	C2
5	Facultad de Química	1	1	32.05	29.69	29.69	20.72	C2
6	Pajalillos	1	1	16.49	12.01	12.01	9.34	C2
7	Isamar	1	1	20.11	14.45	14.45	11.36	C2
8	Garimba	2	2	45.64	43.09	43.09	24.88	C3
9	Ayto. Puerto Cruz	1	1	16.75	11.13	11.13	9.05	C2
10	Botánico	1	1	16.35	11.51	11.51	9.14	C2
11	Montañeta	1	1	16.33	11.35	11.35	7.64	C2
12	Buenavista	1	1	19.70	13.44	13.44	11.56	C2
13	El Palmar	1	1	21.91	12.25	12.25	12.30	C2
14	Las Raíces	1	1	20.78	15.00	15.00	11.98	C2
15	Izaña	1	1	5.44	2.43	2.43	2.34	C2
16	Unelco Caletillas	2	2	35.36	22.39	22.39	10.36	C3
17	La Planta	1	1	21.70	14.82	14.82	13.09	C2
18	La Oficina	1	1	25.12	17.05	17.05	16.67	C2
19	El Bueno	1	1	27.54	16.00	16.00	11.67	C2
20	Unelco Granadilla	3	3	103.13	51.43	51.43	58.43	C5
21	Los Cristianos	1	1	18.69	13.56	13.56	4.37	C2
22	Vilaflores	1	1	-	-	-	-	C2
23	Cueva del Polvo	1	1	17.36	13.68	13.68	11.80	C2
24	Guía de Isora	1	1	17.15	17.56	17.56	11.71	C2
25	San Sebastián	1	1	26.93	19.81	19.81	17.04	C2
26	Valle Gran Rey	2	2	33.70	22.95	22.95	20.67	C3
27	El Cedro	1	1	21.52	16.10	16.10	13.49	C2
28	Valverde	3	3	239.23	141.87	141.87	-	C5
29	Aeropuerto de El Hierro	3	3	250.18	225.59	225.59	-	C5
30	Aeropuerto de La Palma	2	2	49.43	24.44	24.44	15.40	C3
31	El Paso	1	1	27.46	12.48	12.48	9.32	C2
32	Puerto Naos	1	1	19.60	14.27	14.27	11.39	C2
33	Los Llanos	1	1	14.33	8.89	8.89	7.33	C2
34	Fuencaliente	1	1	26.18	16.95	16.95	12.59	C2
35	San Andrés y Sauces	1	1	21.20	13.00	13.00	9.07	C2

Legend: G = Grouping according the corrosion category; D = value of the qualitative variable; Corrosion category: according to ISO 9223 norm.

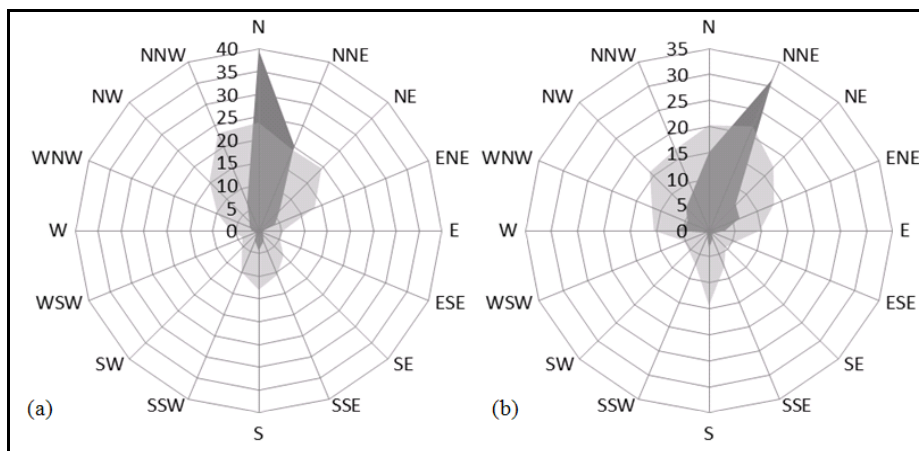


Figure 2. Compass cards corresponding to stations: (a) 29 and (b) 30. (■) Frequency (%), (■) Wind speed (km h^{-1}). They have been composed using data supplied by the National Meteorological Agency of Spain.

Table 3. Values of the k_i coefficients in equations (1) – (4).

Variables	Equation (1)	Equation (2)	Equation (3)	Equation (4)
Constant	3.6660* (0.0824)	3.3553* (0.0501)	3.0974* (0.0452)	2.8319* (0.0291)
<i>EXPT</i>	-0.4310* (0.0497)	-0.3957* (0.0288)		
<i>LEXPT</i>			-0.4863* (0.0562)	-0.4575* (0.0319)
<i>D2</i>		0.6874* (0.0737)		0.6901* (0.0723)
<i>D3</i>		1.9835* (0.0965)		2.0046* (0.0945)
\bar{R}^2	0.2400	0.7465	0.2390	0.7563
<i>N</i>	236	236	236	236

Standard errors are given within brackets below the estimated coefficients.

* Significant at 1% level. ** Significant at 5% level. *** Significant at 10% level.

In order to illustrate the variability of the environmental parameters encountered in the different test sites, Table 4 gives their values for some selected exposure times. Though a linear dependence of the corrosion rates on both the duration of exposure and the time of wetness apparently held at short exposure, no clear relationships could be established with the other parameters. This finding was previously reported in a study of the atmospheric corrosion of zinc [14]. Nevertheless, fit quality was greatly improved with the introduction of the qualitative coefficients in the equations. Correlation ratios amounting to 0.7465 and 0.7563 were obtained using Equations (2) and (4), respectively.

As for the wind, Figure 2 depicts the wind roses for sites 29 and 30 at the time of the collections. Dominant winds from the N-NNW were monitored, which are the Trade Winds. The average speed was $12 \text{ km}\cdot\text{h}^{-1}$, and it remained below $24 \text{ km}\cdot\text{h}^{-1}$ at all times.

Table 4. Amounts of pollutants and TOW values determined over 3 years exposure at each corrosion site.

Site	Cl ($\text{g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$)			SO ₂ ($\text{g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$)			TOW (year)		
	Duration of exposure (month)								
	12	24	36	12	24	36	12	24	36
1	4.77	6.25	5.15	2.51	2.76	2.14	0.14	0.34	0.48
2	5.23	6.65	5.90	2.97	2.25	1.74	0.14	0.34	0.48
3	11.32	11.94	12.96	2.28	1.81	1.31	0.18	0.33	0.54
4	6.03	7.38	5.92	2.21	1.60	1.10	0.59	1.01	1.79
5	6.29	8.06	6.64	2.43	1.63	1.33	0.59	1.01	1.79
6	6.56	7.49	6.72	1.55	0.98	0.66	0.55	0.89	1.53
7	5.33	6.90	5.76	1.85	1.16	0.80	0.60	1.13	2.07
8	8.40	8.81	7.41	1.79	1.20	0.80	0.68	1.16	1.90
9	12.65	12.20	10.34	1.60	1.00	0.71	0.43	0.76	1.28
10	5.72	6.55	5.45	0.99	0.62	0.46	0.50	1.09	1.43
11	4.41	6.07	5.21	0.41	0.29	0.29	0.50	1.09	1.43
12	6.63	8.35	8.32	1.02	0.65	0.95	0.39	0.47	0.96
13	6.32	6.62	5.89	0.84	0.64	0.44	0.39	0.47	0.96
14	5.03	5.46	5.02	1.00	0.95	0.71	0.58	1.05	1.72
15	5.31	3.85	2.66	0.44	0.38	0.40	0.05	0.09	0.17
16	15.10	13.39	11.24	1.69	1.42	1.62	0.32	0.66	1.23
17	9.35	9.54	7.91	1.05	0.86	0.64	0.32	0.66	1.23
18	11.75	10.82	9.58	1.44	1.38	1.03	0.32	0.66	1.23
19	6.23	6.87	5.67	1.11	0.77	0.60	0.57	1.07	1.50
20	63.66	48.34	43.63	2.01	1.56	1.87	0.24	0.42	0.77
21	8.06	9.71	8.42	1.14	0.85	0.60	0.24	0.42	0.77
22	4.83	3.50	2.42	0.72	0.48	0.33	0.34	0.79	1.25
23	9.64	9.11	7.38	0.83	0.66	0.49	0.30	0.48	0.75
24	7.29	6.56	5.09	2.01	1.31	0.79	0.35	0.59	0.94
25	7.31	8.42	6.57	1.29	0.95	0.68	0.35	0.59	0.94
26	11.35	12.45	8.54	1.58	1.30	0.98	0.52	1.13	1.86
27	5.36	6.42	5.02	0.49	0.41	0.26	0.77	1.36	2.25
28	9.10	9.20	6.66	1.07	0.98	0.66	0.45	0.86	1.56
29	134.4	109.6	86.73	3.31	2.90	1.98	0.21	0.35	0.89
30	15.83	14.84	10.54	1.28	0.90	0.62	0.27	0.49	0.97
31	6.02	7.01	5.11	0.42	0.40	0.33	0.26	0.54	1.02
32	12.42	9.70	6.71	1.21	0.92	0.62	0.49	0.74	1.27
33	5.53	6.60	4.81	0.49	0.38	0.26	0.49	0.91	1.48
34	7.91	8.60	6.33	0.73	0.56	0.40	0.25	0.72	1.30
35	6.20	6.73	4.83	0.49	0.37	0.26	0.49	0.91	1.48

Next, the effect of the environmental parameters on the corrosion rates was explicitly introduced in Equations (5) and (7). The concentrations of chloride and SO₂, time of wetness, and interactions between these variables were considered. The corresponding fit outcomes are listed in Table 5. Correlation ratios are 0.7100 in the case of Equation (5) and 0.4871 for Equation (7).

Table 5. Values of the k_i coefficients in equations (5–9).

Variables	Equation (5)	Equation (6)	Equation (7)	Equation (8)	Equation (9)
Constant	2.8222* (0.0965)	3.1119* (0.0669)	2.5207* (0.2690)	3.3847* (0.2105)	3.1446* (0.0570)
SO ₂	0.2735* (0.0505)	0.1532*** (0.0354)			0.1425** (0.0333)
CL	0.0495* (0.0074)	-0.0116* (0.0062)	0.0114* (0.0043)	0.0066** * (0.0034)	-0.0126* (0.0061)
(SO ₂)(CL)	-0.0095* (0.0025)	0.0522* (0.0019)			0.0561* (0.0018)
LEXPT	-1.0191* (0.0982)	-0.7976* (0.0674)			-0.7551* (0.0526)
LSO ₂			0.0218 (0.0612)	0.0422 (0.0464)	
LCL			0.3161** (0.1355)	-0.1801** * (0.1076)	
LTOW	0.4620* (0.0528)	0.3959* (0.0359)	0.1249** * (0.0648)	0.1526* (0.0484)	0.4018* (0.0353)
(SO ₂)(LEXPT)	-0.0846 (0.0725)	-0.1631* (0.0486)	-0.3179* (0.0606)	-0.2951* (0.0454)	-0.1667* (0.0482)
(CL)(LEXPT)	0.0084 (0.0086)	0.0038 (0.0057)			
(TOW)(LEXPT)	0.1345 (0.0834)	0.0453 (0.0562)	-0.3467* (0.0988)	-0.3852* (0.0454)	
(SO ₂)(CL)(LEXP T)	0.0006 (0.0032)	0.0045** (0.0021)			0.0057* (0.0008)
D ₂		0.5152* (0.0582)		0.7162* (0.0854)	0.5223* (0.0574)
D ₃		1.8466* (0.1158)		19.205* (0.1581)	1.8551* (0.1153)
\bar{R}^2	0.6985	0.8660	0.4737	0.7074	0.8666
N	236	236	236	236	236

Standard errors are given within brackets below the estimated coefficients.

* Significant at 1% level. ** Significant at 5% level. *** Significant at 10% level.

The main difficulties experienced during the process of modelling arose from the enormous differences occurring for the values of the environmental parameters determined at each place. Thus, they varied between a minimum value of $2.2 \text{ g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$, and a maximum of $147.98 \text{ g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$, for chloride ions. In the case of SO_2 , the values were comprised between 0.05 and $3.62 \text{ g}\cdot\text{m}^{-2}\cdot\text{year}^{-1}$. Analogously, times of wetness changed from 0.17 to 2.25 years.

Table 6. Experimental (CR_{exp}) and estimated (CR_{est}) corrosion rates and corresponding percentage errors. Predicted values were determined by application of equation (9).

Site	Duration of exposure (month)								
	18			24			36		
	CR_{exp}	CR_{est}	error (%)	CR_{exp}	CR_{est}	error (%)	CR_{exp}	CR_{est}	error (%)
1	9.58	28.08	193.10	9.58	28.08	193.10	7.04	12.04	70.95
2	11.32	23.80	110.20	11.32	23.80	110.20	8.64	11.58	33.94
3	12.96	32.11	147.68	12.96	32.11	147.68	11.75	17.28	47.02
4	14.96	29.40	96.53	14.96	29.40	96.53	12.96	16.03	23.66
5	29.69	32.30	8.80	29.69	32.30	8.80	20.72	18.12	-12.58
6	12.01	21.05	75.25	12.01	21.05	75.25	9.34	13.43	43.79
7	14.45	24.51	69.58	14.45	24.51	69.58	11.36	15.42	35.66
8	43.09	47.48	10.18	43.09	47.48	10.18	24.88	26.71	7.34
9	11.13	24.71	121.91	11.13	24.71	121.91	9.05	14.34	58.51
10	11.51	18.67	62.18	11.51	18.67	62.18	9.14	11.93	30.50
11	11.35	16.40	44.43	11.35	16.40	44.43	7.64	11.44	49.73
12	13.44	14.33	6.60	13.44	14.33	6.60	11.56	13.52	16.93
13	12.25	13.60	10.97	12.25	13.60	10.97	12.30	10.27	-16.50
14	15.00	20.12	34.20	15.00	20.12	34.20	11.98	13.62	13.68
15	2.43	6.08	150.17	2.43	6.08	150.17	2.34	4.78	104.26
16	22.39	59.28	164.76	22.39	59.28	164.76	10.36	44.09	325.70
17	14.82	19.52	31.74	14.82	19.52	31.74	13.09	12.76	-2.48
18	17.05	29.24	71.51	17.05	29.24	71.51	16.67	16.58	-0.50
19	16.00	20.64	28.96	16.00	20.64	28.96	11.67	12.91	10.61
21	13.56	16.14	18.98	13.56	16.14	18.98	4.37	10.51	140.52
23	13.68	14.97	9.50	13.68	14.97	9.50	11.80	9.70	-17.85
24	17.56	20.15	14.78	17.56	20.15	14.78	11.71	11.07	-5.47
25	19.81	19.36	-2.25	19.81	19.36	-2.25	17.04	11.60	-31.96
26	22.95	67.65	194.74	22.95	67.65	194.74	20.67	31.86	54.13
27	16.10	19.55	21.41	16.10	19.55	21.41	13.49	14.04	4.08
28	141.9	149.8	5.60	141.9	149.8	5.60	-	-	-
30	24.44	38.81	58.81	24.44	38.81	58.81	15.40	21.43	39.18
31	12.48	13.74	10.09	12.48	13.74	10.09	9.32	10.41	11.64
32	14.27	22.25	55.92	14.27	22.25	55.92	11.39	12.87	13.08
33	8.89	16.64	87.24	8.89	16.64	87.24	7.33	11.84	61.54
34	16.95	17.18	1.39	16.95	17.18	1.39	12.59	11.87	-5.71
35	13.00	16.61	27.84	13.00	16.61	27.84	9.07	11.87	30.88

A major improvement results again from the introduction of the qualitative coefficients in the equations. Equations (6) and (8) delivered correlation ratios of 0.8660 and 0.7074, respectively, which are better than any obtained before. A simplification of the best mathematical model was finally attempted. It consisted in the removal of the non-significant variables according to Table 5. The concerned variables were (*CL*), (*LEXPT*) and (*TOW*)(*LEXPT*). As a result, the mathematical model given by equation (9) was derived:

$$\ln(CR) = 3.1446 + 0.1425(SO_2) - 0.0126(CL) + 0.4018\ln(TOW) + 0.0561(SO_2)(CL) - 0.7551\ln(TEXP) - 0.1667(CL)\ln(TEXP) + 0.0057(SO_2)(CL)\ln(TEXP) + 0.5223D_2 + 1.8551D_3 \quad (9)$$

In order to check the validity of the new mathematical model, corrosion rates for 18, 24 and 36 months exposures were predicted for all the considered test sites. Table 6 lists both the experimental and the predicted values, and the corresponding errors were determined. It can be observed that the magnitude of the errors greatly diminishes with the elapse of time. It is noticed that for the longest exposure having experimental data available, namely 3 years, errors below 25% occur in 51% of the test sites, whereas the ratio exceeds 80% when errors up to 50% were considered instead (see Table 7).

Table 7. Percentages of corrosion sites with errors in the percentile intervals.

Error interval (%)	Percentage of corrosion sites		
	18 months	24 months	36 months
0-25	37.5	37.5	51.6
25-50	15.6	15.6	29.0
50-75	15.6	15.6	9.7
75-100	9.5	9.4	0
>100	21.9	21.9	9.7

5. Conclusions

Mathematical modelling of the atmospheric corrosion of carbon steel in the fragmented subtropical territory conformed by the four islands in the province of Santa Cruz de Tenerife (Canary Islands, Spain) was a complex task due to the wide variety of microclimates present. Equations containing the duration of exposure as the only explanatory variable failed to estimate corrosion rates that can be correlated with the experimental results from outdoor exposures. A significant improvement in fit quality was found with the introduction of semi-empiric coefficients related to atmospheric observations performed over a short period of time. Yet the errors involved in those estimations were unacceptably high. A definite improvement requires the use of certain environmental parameters, namely the time of wetness, and the deposition rates of chloride ions and sulphur dioxide at every location as explanatory variables in the equations in addition to the time of exposure. The

obtained mathematical model produces estimates of the corrosion rates that satisfactorily match the majority of the experimental observations for longer exposures.

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