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# Development of Mathematical Models to predict the Atmospheric Corrosion Rate of Carbon Steel in Fragmented Subtropical Environments

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Mathematical modelling of atmospheric corrosion based on the aggressiveness categories defined by standard ISO 9223 greatly fail to predict the actual corrosion rates of metals in subtropical environments. Therefore, new concepts for modelling are required as to adequately predict corrosion rates from environmental factors such as the deposition rate of chemical agents (namely chloride and sulphur dioxide), climate effects (such as moisture and time of wetness), and the duration of metal exposure. The novel methodology is based on the definition of a set of qualitative variables to distribute locations exhibiting distinctive initial characteristics towards metal corrosion. The validity of the method was checked by using data obtained during three years of exposure of carbon steel in 74 stations distributed along the seven main islands of the Canary Islands (Spain). A definite evaluation of the impact of environmental factors on the extent of corrosion was achieved, and good results were defined in terms of fitting quality.

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**Keywords:** Atmospheric corrosion, carbon steel, subtropical region, mathematical model.

## 1. INTRODUCTION

Atmospheric corrosion is a problem of great interest, mainly due to high costs arising from failure and leakage, disruption in service and operation, maintenance and renovation, environmental pollution from leakage of hazardous materials and corrosion products, and replacement of infrastructure, utilities, industrial operation, transportation, materials storage, transmission lines, etc. In a study about the cost of corrosion, undertaken by CC Technologies Laboratories, Inc. with support from the FHWA and NACE between 1999 and 2001, it was determined that the annual cost due to direct corrosion would be in the order of ca. 3.1% of GNP [1]. Generically, it is estimated that the total cost due to corrosion amounts between 4-5% of the gross domestic product of a country, being the atmospheric corrosion the main factor that influences that cost [2-4]. The characterization of the aggressiveness of a particular atmosphere, is therefore a topic of major interest since its knowledge and application of adequate prevention measures presume a considerable cost saving.

For this reason numerous research programs were conducted in several countries, aimed to characterize atmospheric corrosion in various geographical areas. A major objective of those studies was to obtain mathematical models for the prediction of the degradation rate of the exposed metal in a wide geographical area. As a result, several models were developed that predict the corrosion rate. Among them, the ISO CORRAG model supported by NACE [5,6], and the models obtained by The International Cooperative Program on Effects and The Iberoamerican Atmospheric Corrosion Map Project MICAT (Mapa Iberoamericano de Corrosión Atmosférica) [7] are applied extensively. The same effort was performed in Spain with the objective to derive a map of corrosivity for the whole country. As a result, corrosivity maps are available in regions such as Galicia, Catalonia, the Basque Country, Andalusia and Extremadura [8]. Despite the diversity of working parties, they all performed the classification of environments in terms of corrosion rates pursuant to ISO 9223 [9]. A similar approach was also attempted in smaller geographical areas of subtropical character [10,11], but it was found that the ISO 9223 norm presented major limitations as to account for the experimental corrosion rates [12].

Therefore, a project has been funded to elaborate the Corrosivity Map of the Canary Islands, a fragmented subtropical region directly affected by oceanic conditions. The Canarian Archipelago is a group of seven islands in the Atlantic Ocean, near the African coast (see Figure 1). The islands are distributed between latitudes 27º and 29º North, covering an area of approximately of 7,447 km$^2$ surrounded by 1,583 km shoreline. The Canary Islands conforms a rather unique geographic location, because six distinct microclimates have been characterized in this small stretch of land. More interestingly, though the microclimates are differently distributed among the islands, all of them can be found simultaneously in the case of Tenerife Island, whereas five of them are found in Gran Canaria Island. The variety of microclimates is a major cause for the observation of atmospheric corrosion rates that can be ascribed to any of the proposed corrosive categories ranging from those specific to tropical areas, to marine, industrial and even rural environments. The first stage of the project was directed to determine the distribution of atmospheres existing in the archipelago, and to quantify their aggressiveness by exposing several metals of extensive industrial use such as carbon steel, galvanized steel, zinc, copper and aluminium. In order to cover the widest possible variety of environments, 74 test stations were distributed along the seven islands (Tenerife, La Palma, La Gomera, El Hierro, Gran Canaria, Fuerteventura and Lanzarote). The location and characteristics of the 74 sites have been given in previous work, together with the corrosivity categories relative to carbon steel, zinc and copper degradation that were assigned to each place [10,12,13]. At present, the corrosion rates for the investigated materials have been determined at each location with high reproducibility, whereas it was observed that the mathematical models available in the scientific literature do not satisfactorily describe and predict those experimental corrosion rates. Therefore, new mathematical models must be derived to predict the corrosion rate of metallic materials in fragmented subtropical environments such as those occurring in the Canary Islands.

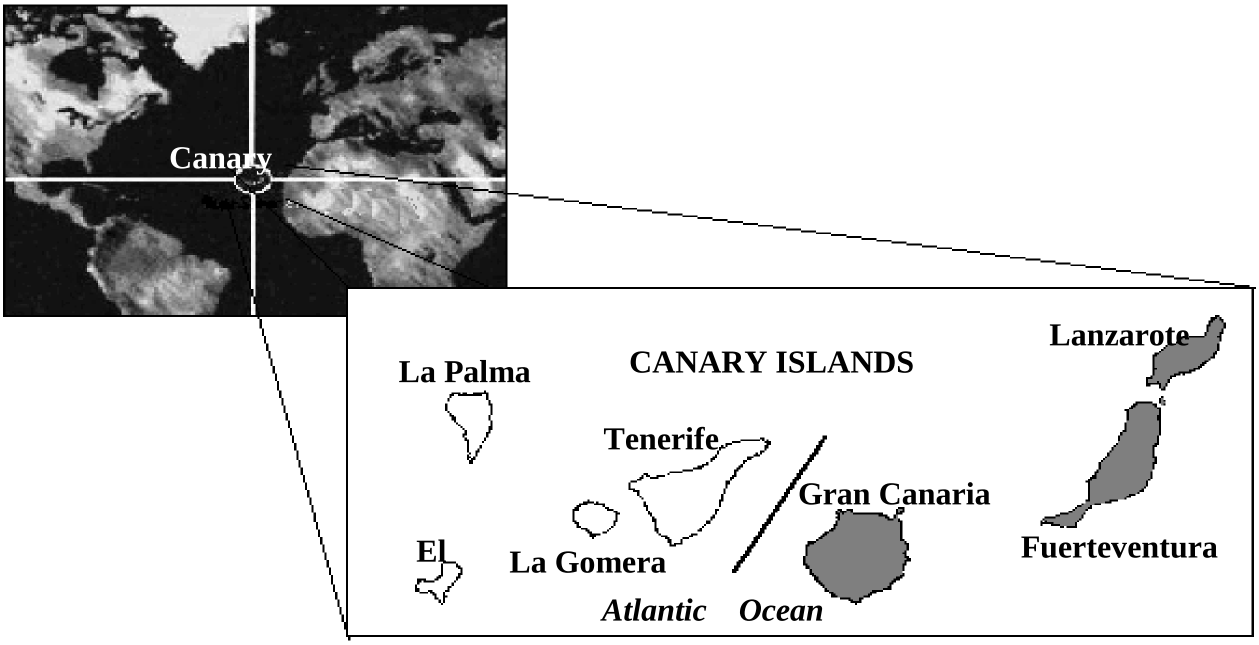

**Figure 1.** Geographical location of the Canary Islands (Spain). The islands are distributed in two provinces for political administration: Santa Cruz de Tenerife is composed by the four islands at the West (Tenerife, Gomera, La Palma and El Hierro), and Las Palmas de Gran Canaria by the remaining three islands (Gran Canaria, Fuerteventura and Lanzarote).

In this work we report the process undertaken to develop models for the atmospheric corrosion of carbon steel. Firstly, we proceeded to derive empirical corrosion equations for either single sites or groups of stations with the same category of corrosion in a given island. In this way, models with good regression ratios were obtained but their applicability was restricted to very small geographical areas within the same island. In that process, the first model tested was the power law [14], widely used in studies of atmospheric corrosion. Unfortunately, this equation leads to major discrepancies with experimental data in the subtropical environments of the Canary Islands. Next, modified models [11] based on a new expansion of the power law exponent $n$ containing the distributed time of wetness (TOW) and the concentrations of pollutants were tested. Alternately, equations containing qualitative variables were introduced with the intention to alleviate the problem originating from test sites exhibiting a wide variety of corrosion categories [10]. Rather good results were attained using those models, thus subsequent work was directed to the extension of those methods to describe the entire archipelago, i.e., in order to derive more general models that can be applied in all the islands by taking carbon steel as the model metallic system.

## 2. EXPERIMENTAL

The 74 test sites consisted of a metallic frame on which the metal samples were attached using a nylon screw to avoid the formation of galvanic couples. The pollutant sensors were located at the frame rear. For the determination of sulphur dioxide $SO_2$ pollution, either the candel lead dioxide method under ASTM D 2010-85 [15], or the Husy method according to ISO/TC 156 N 250 norm [16], were employed. Chloride measurements were performed using the wet candle method following the instruct ions of ISO 9225:1992 (E) [17]. Pollutants were collected on a monthly basis.

The composition of carbon steel samples is shown in Table 1. Plates of approximate dimensions: 100 x 40 x 20 $mm^3$ were employed. Before being placed in the corresponding stations, the samples were marked for identification, cleaned according to the ASTMG G1-90 norm [18], subsequently measured and weighed. Samples were collected from the test sites at various durations of exposure, namely 3, 6, 9, 12, 18, 24, and 36 months. Corrosion products were removed by chemical operation as described by the ISO/DIS 8403.3 [19]. The evaluation of the corrosion rate was made by weight loss of the samples. After the samples were cleaned and dried, they were weighed again. Corrosion rates were evaluated from weight loss measurements.

**Table 1.** Composition of carbon steel test sheets used in this study.

| | Metal Composition (wt.%) | | | | | |
|---|---|---|---|---|---|---|
| | Si | Fe | C | Mn | P | S |
| Carbon steel | 0.080 | 99.467 | 0.060 | 0.370 | 0.009 | 0.014 |

The time of wetness (TOW) was determined from the data collected using relative humidity hygrometers placed in a small cabinet at the rear of the station frames, and they were complemented with data supplied by the National Meteorological Institute of Spain (AEMET, Madrid, Spain). The latter were cumulative values taken over 8 hour-periods in a systematic way, whereas the autonomous hygrometers produced a continuous recording with autonomy for about one month. Data on the speed and direction of wind were kindly supplied by AEMET.

## 3. RESULTS

### *3.1. Concentrations of pollutants and atmospheric conditions*

The distribution of concentrations of chloride ions and sulphur dioxide determined with annual periodicity up to 3 years for the 74 test sites are given in Figures 2 and 3, organized as 39 sites in the three eastern islands constituting the province of Las Palmas de Gran Canaria (namely Gran Canaria, Fuerteventura and Lanzarote), and 35 sites in the remaining four islands conforming the western province of Santa Cruz de Tenerife (i.e., Tenerife, La Palma, Gomera and El Hierro), respectively.

Though the amounts of pollutants show some variations among the annual accumulated values for a given test site, these changes are very small compared to the big variability found between different stations, even among those placed in the same island. Despite the abrupt orography present in the islands, with the highest point reaching up to 3,718 m height in Tenerife Island, measurable chloride concentrations were found at all the sites. The big variations between them should be related to climate conditions imposed by the dominating wind regimes and the amount of humidity occurring at each place.

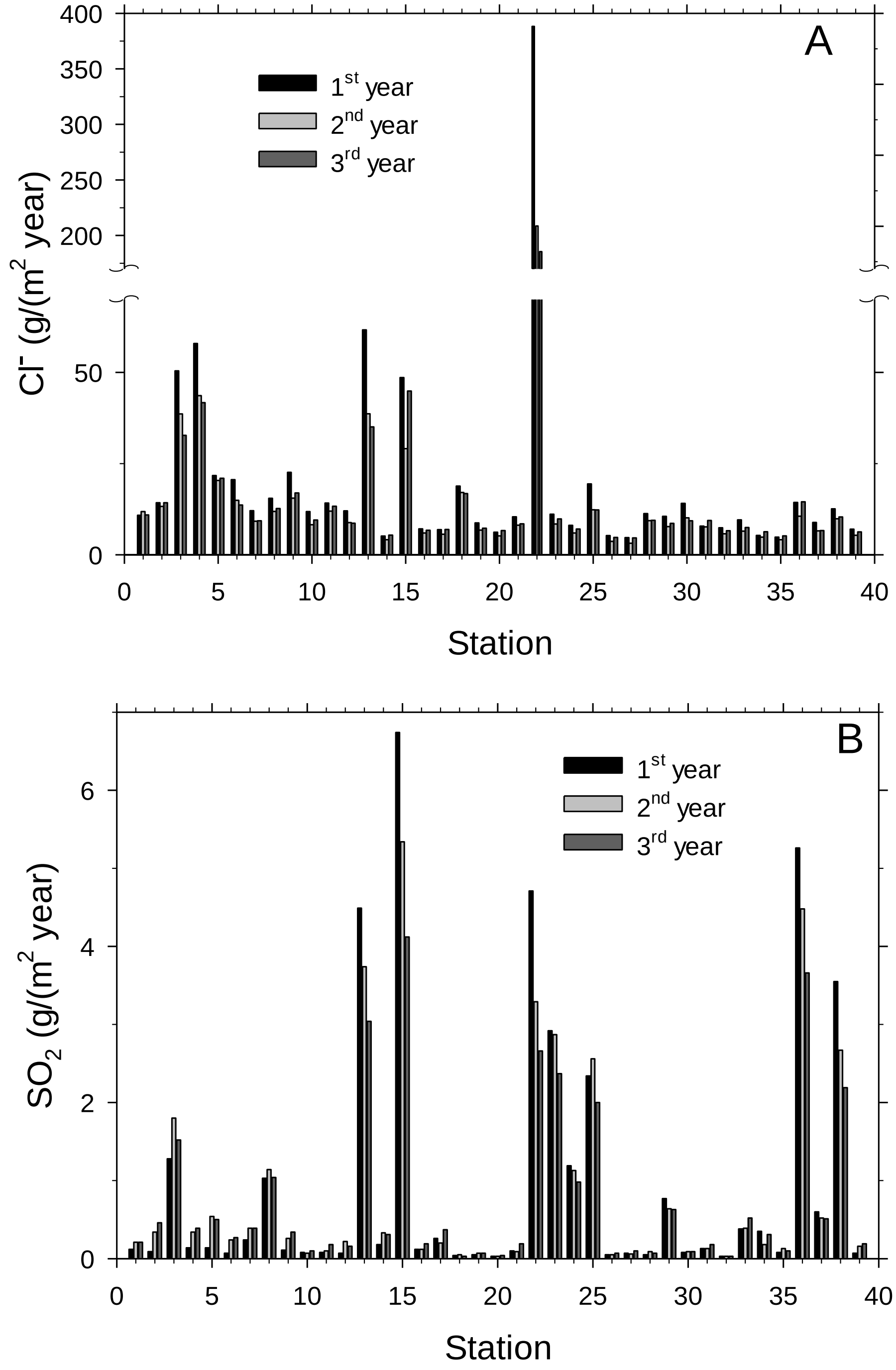

**Figure 2.** Temporal variations of pollutant concentrations collected in the test sites planted in the eastern province (i.e., Las Palmas de Gran Canaria, GC). Number of sites: *N* = 39. Pollutants: (A) chloride, and (B) sulphur dioxide.

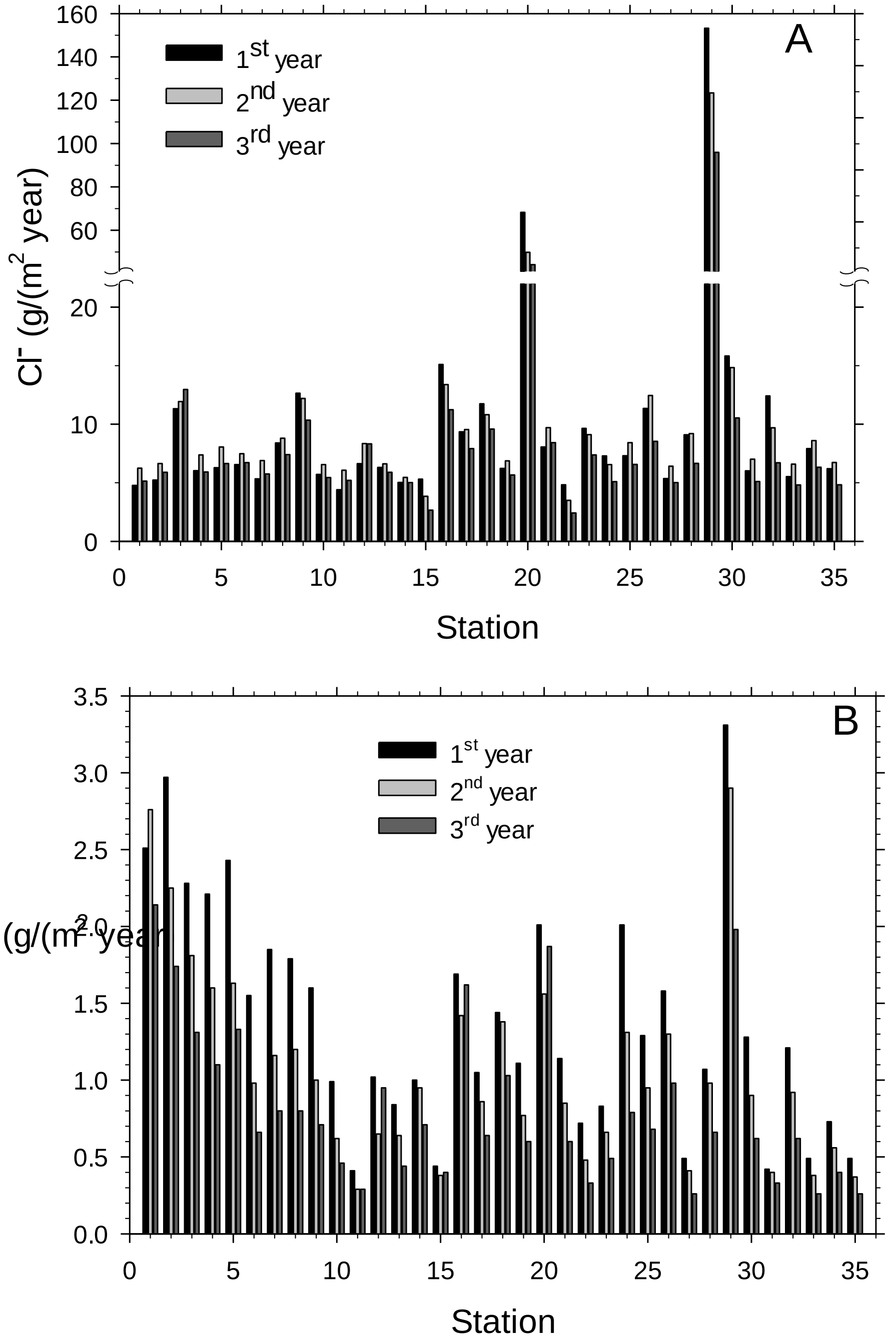

**Figure 3.** Temporal variations of pollutant concentrations collected in the test sites established in the western province (i.e., Santa Cruz de Tenerife, TF). Number of sites: *N* = 35. Pollutants: (A) chloride, and (B) sulphur dioxide.

Therefore, both time of wetness, and wind direction and speed, were considered in this work. Time of wetness distributions are plotted in Figure 4, whereas Figure 5 shows the compass cards depicting wind direction frequency (%) and speed (km/h) that correspond to stations LP-25 and TF-5, given for illustration. These plots show the predominance of Trade Winds blowing mainly in the Northeast direction, which carry a great amount of salinity. Finally, the sites exhibiting high $SO_2$ collections are associated with areas of major human activity, mainly associated with the industrial poles usually built in the neighbourhood of either power generation stations or airports.

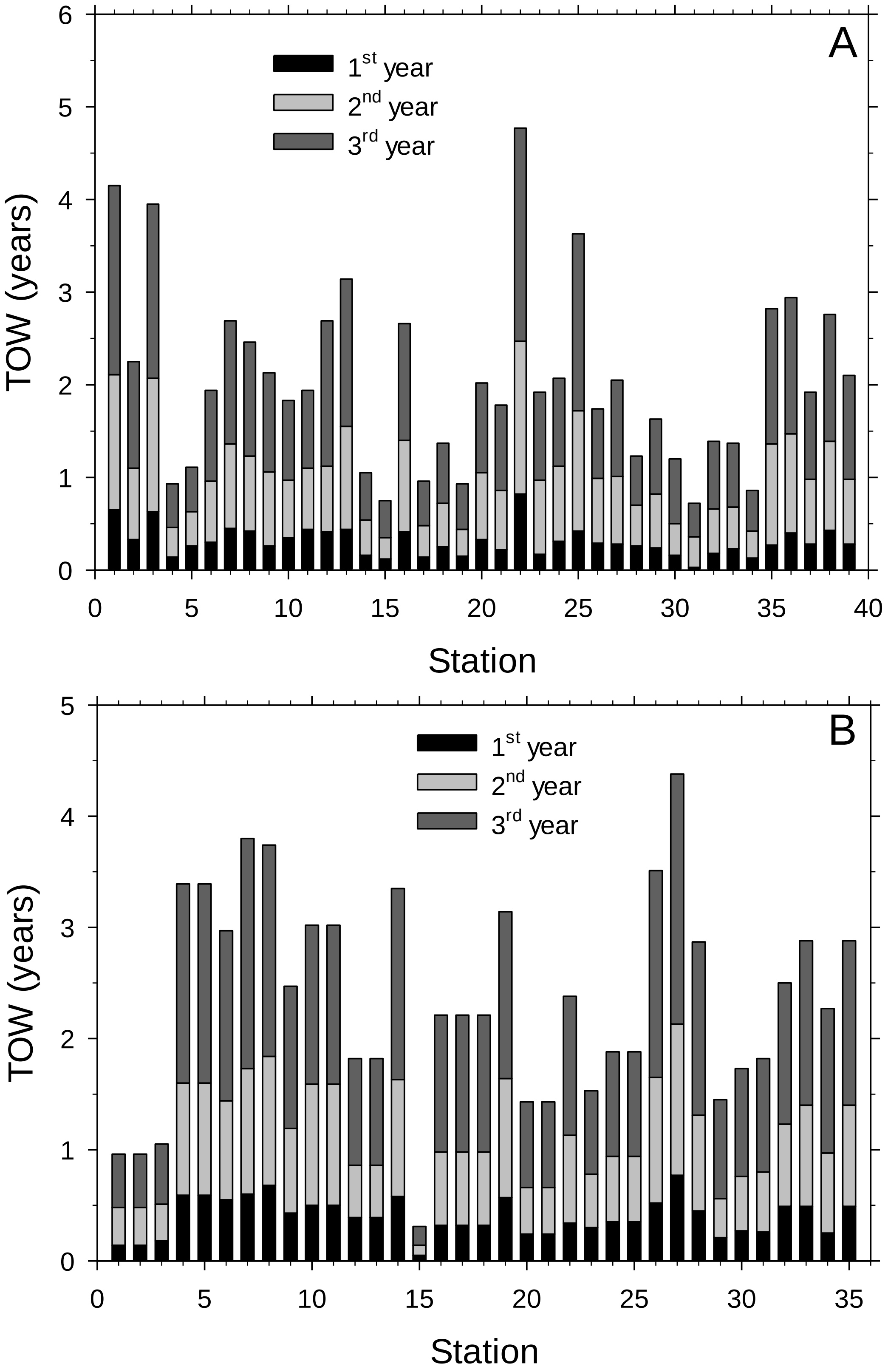

**Figure 4.** Temporal variation of time of wetness (TOW) collected in the test sites established in (A) the eastern province (Las Palmas de Gran Canaria, GC), and (B) the western province (Santa Cruz de Tenerife, TF).

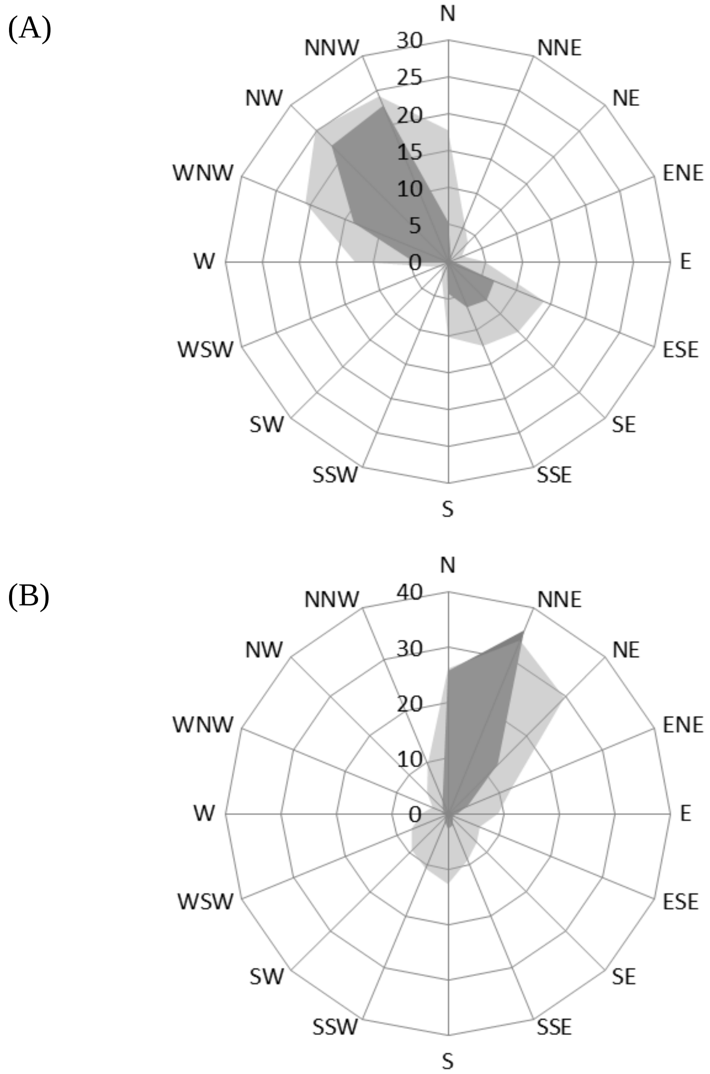

**Figure 5.** Compass cards corresponding to stations (A) LP-25, and (B) TF-5. (■)Frequency (%), and (□) wind speed (km/h). They have been assembled using data supplied by the National Meteorological Agency of Spain.

### *3.2. Corrosion models*

In order to account for the variability in the aggressiveness of the environments present in the geographical area considered, the test sites were grouped according to the different corrosive categories that could be assigned to each place. Thus, the groups were organized to account for the characteristics described in each province as it follows: group $G1$ corresponds to stations with corrosivity category C2; group $G2$ corresponds with corrosivity category C3; group $G3$ corresponds to corrosivity category C4 in the province of Las Palmas, and to both C4 and C5 in the province of Santa Cruz de Tenerife; finally group $G4$ corresponds to corrosivity category C5 in the province of Las Palmas. In order to facilitate mathematical modelling, numeric values were assigned to these groups as it follows: $D1 = 1$ for an observation from grouping $G1$, whereas $D1 = 0$ for the remaining cases; $D2 = 1$ for grouping $G2$, and $D2 = 0$ for the remaining cases; $D3 = 1$ for grouping $G3$, and $D3 = 0$ for the remaining cases; $D4 = 1$ for an observation from grouping $G4$, and $D4 = 0$ for the remaining cases.

Table 2 lists the corrosion rates measured for carbon steel with annual periodicity, the corrosivity category assigned according to ISO 9223 norm, as well as the group and value of the qualitative variable $D_i$ for each site.

**Table 2.** Groupings established on the basis of corrosivity categories, and corresponding corrosivity category determined from weight loss measurements for carbon steel, for the stations covered in this work.

| | Las Palmas (LP) | | | | | Santa Cruz de Tenerife (TF) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Station No. | G | Corrosion rate (μm/year) | | | C | G | Corrosion rate (μm/year) | | | C |
| | | 1st year | 2nd year | 3rd year | | | 1st year | 2nd year | 3rd year | |
| 1 | 1 | 13.54 | 9.49 | 8.42 | C2 | 1 | 14.12 | 9.58 | 7.04 | C2 |
| 2 | 2 | 30.19 | 23.55 | 27.13 | C3 | 1 | 17.45 | 11.32 | 8.64 | C2 |
| 3 | 4 | 299.98 | 73.08 | 137.58 | C5 | 1 | 16.73 | 12.96 | 11.75 | C2 |
| 4 | 3 | 75.36 | 68.36 | 46.07 | C4 | 1 | 26.83 | 14.96 | 12.96 | C2 |
| 5 | 1 | 16.62 | 12.30 | 12.20 | C2 | 1 | 32.05 | 29.69 | 20.72 | C2 |
| 6 | 1 | 24.93 | 23.60 | 39.74 | C2 | 1 | 16.49 | 12.01 | 9.34 | C2 |
| 7 | 2 | 25.66 | 18.67 | 13.27 | C3 | 1 | 20.11 | 14.45 | 11.36 | C2 |
| 8 | 2 | 33.52 | 22.20 | 17.82 | C3 | 2 | 45.64 | 43.09 | 24.88 | C3 |
| 9 | 1 | 16.60 | 12.42 | 15.14 | C2 | 1 | 16.75 | 11.13 | 9.05 | C2 |
| 10 | 2 | 30.00 | 26.97 | 20.71 | C3 | 1 | 16.35 | 11.51 | 9.14 | C2 |
| 11 | 3 | 76.57 | 55.96 | 61.73 | C4 | 1 | 16.33 | 11.35 | 7.64 | C2 |
| 12 | 1 | 20.86 | 15.75 | 16.03 | C2 | 1 | 19.70 | 13.44 | 11.56 | C2 |
| 13 | 3 | 61.74 | 44.37 | 49.57 | C4 | 1 | 21.91 | 12.25 | 12.30 | C2 |
| 14 | 1 | 19.48 | 13.05 | 11.58 | C2 | 1 | 20.78 | 15.00 | 11.98 | C2 |
| 15 | 3 | 61.99 | 39.73 | 28.07 | C4 | 1 | 5.44 | 2.43 | 2.34 | C2 |
| 16 | 1 | 16.68 | 12.85 | 22.64 | C2 | 2 | 35.36 | 22.39 | 10.36 | C3 |
| 17 | 1 | 18.20 | 18.64 | 19.44 | C2 | 1 | 21.70 | 14.82 | 13.09 | C2 |
| 18 | 1 | 24.79 | 25.51 | 32.36 | C2 | 1 | 25.12 | 17.05 | 16.67 | C2 |
| 19 | 1 | 12.38 | 8.68 | 6.64 | C2 | 1 | 27.54 | 16.00 | 11.67 | C2 |
| 20 | 2 | 30.40 | 22.50 | 29.25 | C3 | 3 | 103.13 | 51.43 | 58.43 | C5 |
| 21 | 1 | 20.52 | 14.47 | 24.77 | C2 | 1 | 18.69 | 13.56 | 4.37 | C2 |
| 22 | 4 | 222.33 | 157.05 | 145.78 | C5 | 1 | - | - | - | C2 |
| 23 | 2 | 34.27 | 24.92 | 36.77 | C3 | 1 | 17.36 | 13.68 | 11.80 | C2 |
| 24 | 2 | 32.73 | 22.36 | 25.76 | C3 | 1 | 17.15 | 17.56 | 11.71 | C2 |
| 25 | 2 | 29.61 | 23.41 | 23.19 | C3 | 1 | 26.93 | 19.81 | 17.04 | C2 |
| 26 | 1 | 19.35 | 13.69 | 10.75 | C2 | 2 | 33.70 | 22.95 | 20.67 | C3 |
| 27 | 1 | 10.47 | 7.01 | 12.85 | C2 | 1 | 21.52 | 16.10 | 13.49 | C2 |
| 28 | 2 | 27.66 | 21.91 | 41.20 | C3 | 3 | 239.23 | 141.87 | - | C5 |
| 29 | 1 | 23.97 | 23.21 | 22.95 | C2 | 3 | 250.18 | 225.59 | - | C5 |
| 30 | 1 | 16.18 | 12.19 | 15.69 | C2 | 2 | 49.43 | 24.44 | 15.40 | C3 |
| 31 | 1 | 15.21 | 8.38 | 7.62 | C2 | 1 | 27.46 | 12.48 | 9.32 | C2 |
| 32 | 1 | 12.15 | 9.07 | 6.40 | C2 | 1 | 19.60 | 14.27 | 11.39 | C2 |
| 33 | 1 | 19.64 | 14.49 | 16.50 | C2 | 1 | 14.33 | 8.89 | 7.33 | C2 |
| 34 | 2 | 30.06 | 27.11 | 20.41 | C3 | 1 | 26.18 | 16.95 | 12.59 | C2 |
| 35 | 1 | 14.00 | 12.96 | 11.26 | C2 | 1 | 21.20 | 13.00 | 9.07 | C2 |
| 36 | 2 | 44.81 | 28.07 | 41.20 | C3 | | | | | |
| 37 | 2 | 27.51 | 22.85 | 25.52 | C3 | | | | | |
| 38 | 2 | 50.28 | 43.70 | 56.34 | C3 | | | | | |
| 39 | 1 | 23.97 | 15.59 | 15.77 | C2 | | | | | |

Legend:
G = Group according the corrosion category
C = Corrosion category according to ISO 9223 norm

The mathematical models considered in this work are listed next:

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

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

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

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

$$\begin{aligned}\ln(CR) = {} & k_0 + k_1(SO2) + k_2(CL) + k_3 \ln(TOW) + k_4(SO2)(CL) + k_5 \ln(TEXP) + k_6(SO2)\ln(TEXP) + \\ & + k_7(CL)\ln(TEXP) + k_8(SO2)(CL)\ln(TEXP) + k_9(TOW)\ln(TEXP)\end{aligned} \tag{5}$$

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

$$\ln(CR) = k_0 + k_1 \ln(SO2) + k_2 \ln(CL) + k_3 CL + k_4 \ln(TOW) + k_5(SO2)\ln(TEXP) + k_6(TOW)\ln(TEXP) \tag{7}$$

$$\begin{aligned}\ln(CR) = {} & k_0 + k_1 \ln(SO2) + k_2 \ln(CL) + k_3 CL + k_4 \ln(TOW) + k_5(SO2)\ln(TEXP) + k_6(TOW)\ln(TEXP) \\ & + \delta_2 D2 + \delta_3 D3 + \delta_4 D4\end{aligned} \tag{8}$$

where *CR* is the corrosion rate expressed in μm/year; *TEXP*, the exposure time (year); *TOW*, time of wetness (year); *CL*, concentration of chlorides (g/m$^2$ year); and *SO*2, concentration of $SO_2$ (g/m$^2$ year). The qualitative variables (*D*2, *D*3, and *D*4) were included in equations (2), (4), (6) and (8) to produce changes in the independent coefficient $k_0$ accounting for the different initial corrosion characteristics associated to the various groups of stations.

## 4. DISCUSSION

Models (1) to (4) will be discussed first, being model (1) the non-linear model proposed by Legault and Parson [14], whereas the others are modifications based on it. In this model it is assumed that the exponent $k_1$ depends on the variables corresponding to the environment [20], and may be developed according to the level of chlorides, $SO_2$ and wetting time [13]. It is readily observable from Table 3 that higher quality fits are attained using models (2) and (4) (i.e., 0.7098 and 0.7553, respectively) compared to models (1) and (3) when the only explanatory variable is the time of exposure. This is a logical result arising from the wide variety of environments present in the Canary Islands, where 5 to 6 clearly differentiated climatic environments can be found on islands such as Gran Canaria and Tenerife, respectively. While it is probable that the corrosion rate may vary linearly with the time of wetness, TOW, because it is some fraction of the actual exposure time of the material, no evident dependences can be established with the remaining environmental factors, as it was demonstrated for zinc in a previous report [10]. Evidently, the huge variations in corrosion rates that can be found in Table 2, cannot be simply accounted for in terms of the corresponding corrosion categories. For instance, even within one island after only one year, the data variations range from 10.47 μm/year (station GC-27) to 299.98 μm/year (station GC-3) in the case of Gran Canaria, and between 3.09 μm/year (station TF-15) to 247.27 μm/year (station TF-29) in the case of Tenerife. Poor fits are then observed when models only consider the duration of exposure to the atmosphere as they do not account for the changes between locations, and cannot be regarded to represent the corrosion characteristics of the islands that form the archipelago. Therefore, several qualitative variables were defined (namely *D2* to *D4* in equations (2) and (4)) in the models as to identify aggressiveness levels from the measurement of weight losses of the coupons collected at each location though measured for an acceptable short period of exposure (typically one year to cover a full season cycle). Subsequently, weight losses were employed to associate a corrosivity category to the location according to standard ISO 9223 (also included in Table 2 for all the locations under consideration). In fact, introduction of the qualitative variables in the mathematical equations significantly improves the fitting power because it accounts for the major distortion caused by very different values of initial corrosion rates. Yet, one cannot recognize the effects that produce different environmental parameters medium on the corrosion rate.

**Table 3.** Values of the $k_i$ constants in models (1) to (4).

| Variables | Model (1) | Model (2) | Model (3) | Model (4) |
|---|---|---|---|---|
| Constant | 3.3666*<br>(0.0408) | 3.0051*<br>(0.0267) | 3.1930*<br>(0.0298) | 2.8187*<br>(0.0204) |
| TEXP | -0.1235*<br>(0.0132) | -0.1333*<br>(0.0076) | | |
| LTEXP | | | -0.3311*<br>(0.0287) | -0.3417*<br>(0.0158) |
| D2 | | 0.6520*<br>(0.0402) | | 0.6374*<br>(0.0369) |
| D3 | | 1.3736*<br>(0.0727) | | 1.3538*<br>(0.0667) |
| D4 | | 2.0540*<br>(0.0717) | | 2.0470*<br>(0.0658) |
| $\bar{R}^2$ | 0.1291 | 0.7098 | 0.1835 | 0.7553 |
| N | 587 | 587 | 587 | 587 |

Standard errors are given within brackets below the value obtained for the coefficient.
$^{*}$ Significant at 1% level. $^{**}$ Significant at 5% level. $^{***}$ Significant at 10% level.

For the sake of comparison, the experimental data obtained in our work were also modelled with those proposed in the scientific literature which correspond to geographical areas with similar weather characteristics to those found in the Canary Islands (high levels of chlorides and TOW, low levels of $SO_2$, and high exposure to the sun's rays), namely MICAT (developed for tropical climates of Latin-America) [21], and that proposed for marine environments along the Gulf of Mexico [22]. In the first case, the corrosion rate was described by:

$$C_{cs} = 2.49 + 1.59\, SO_2 + 0.96\, Cl \qquad (9)$$

where $C_{cs}$ is expressed in micron, and the concentration of chlorides and $SO_2$ in mg/(m$^2$ day). Analogously, the atmospheric corrosion in the Gulf of Mexico was modelled using,

$$C_{cs} = 0.228\, TOW + 0.290\, Cl + 0.410\, SO_2 \qquad (10)$$

where $C_{cs}$ comes in mg/(m$^2$ year), the concentration of chlorides and $SO_2$ in mg/(m$^2$ day), and TOW in hours/year. The results show that both models have high error regarding the corrosion rates estimated for the first year in the two provinces. Though the model proposed by MICAT offers the best fit, only 41% of the stations have an error equal to or less than 50%, while errors greater than 100%

were found for all the test sites using the equation proposed for the Gulf of Mexico. Evidently, neither of the two models describes the atmospheric corrosion behaviour of carbon steel in the Canarian Islands.

For this reason we propose models (5) to (8) where a concentration-dependent chloride, $SO_2$, wetting time and their interaction coefficient were further introduced. It is clearly observed from Table 4 how the models (6) and (8), where qualitative variables have been included, provide better fits compared with models where these variables were not introduced. Therefore, the model (6), which is an extension of the model (5) including qualitative variables, has an regression factor of 0.8012, significantly greater than 0.6354 obtained from model (5), and model (8) delivers 0.6922 whereas model (7) gives 0.5094.

**Table 4.** Values of the $k_i$ constants in models (5) to (8).

| *Variables* | *Model (5)* | *Model (6)* | *Model (7)* | *Model (8)* |
|---|---|---|---|---|
| Constant | 2.8948* | 2.9441* | 1.9904* | 2.5287* |
| | (0.0535) | (0.0416) | (0.1031) | (0.0932) |
| *SO2* | 0.2305* | 0.0719* | | |
| | (0.0186) | (0.0157) | | |
| *CL* | 0.0310* | 0.0010* | 0.0020** | 0.0018** |
| | (0.0019) | (0.0018) | (0.0009) | (0.0079) |
| *(SO2)(CL)* | -0.0056* | -0.0018* | | |
| | (0.0004) | (0.0004) | | |
| *LTEXP* | -0.6555** | -0.6063* | | |
| | (0.0467) | (0.0350) | | |
| *LSO2* | | | 0.1237* | 0.0725* |
| | | | (0.0173) | (0.0140) |
| *LCL* | | | 0.4694* | 0.0823*** |
| | | | (0.0451) | (0.0439) |
| *LTOW* | 0.2276* | -0.2012* | -0.1435* | -0.1499* |
| | (0.0344) | (0.0260) | (0.0283) | (0.0225) |
| *(SO2)(LTEXP)* | 0.0355** | 0.0122 | -0.0379** | -0.0415* |
| | (0.0180) | (0.0134) | (0.0165) | (0.0132) |
| *(CL)(LTEXP)* | 0.0084* | 0.0071* | | |
| | (0.0020) | (0.0015) | | |
| *(TOW)(LTEXP)* | -0.0022 | -0.0055 | -0.0438** | -0.0403* |
| | (0.0158) | (0.0117) | (0.0175) | (0.0139) |
| *(SO2)(CL)(LTEXP)* | -0.0022* | -0.0016* | | |
| | (0.0005) | (0.0004) | | |
| *D*2 | | 0.5544* | | 0.5919* |
| | | (0.0353) | | (0.0439) |
| *D*3 | | 1.1357* | | 1.0538* |
| | | (0.0727) | | (0.0949) |
| *D*4 | | 1.4874* | | 1.6591* |
| | | (0.0901) | | (0.1072) |
| $\bar{R}^2$ | 0.6354 | 0.8012 | 0.5094 | 0.6922 |
| ***N*** | 587 | 587 | 587 | 587 |

Standard errors are given within brackets below the value obtained for the coefficient.
$^{*}$ Significant at 1% level. $^{**}$ Significant at 5% level. $^{***}$ Significant at 10% level.

A further improvement was produced by removing from equation (6) those variables that we consider non significant for the atmospheric corrosion of carbon steel in these environments. In this way, a new model (11) was developed, which is given by:

$$\begin{aligned}\ln(CR) &= 2.9378 + 0.0738(SO2) + 0.0097(CL) + 0.1987\ln(TOW) - 0.0018(SO2)(CL)\\ &-0.5985\ln(TEXP) + 0.0067(CL)\ln(TEXP) - 0.0014(SO2)(CL)\ln(TEXP) + 0.5544\cdot D2\\ &+1.1423D3 + 1.4916D4\end{aligned} \tag{11}$$

The best fits were obtained using equation (11). We regard this model to satisfactorily describe corrosion rates of carbon steel over the complete archipelago. When defining the errors committed by the estimates made with this model along three years of exposure, 34% of the stations have an error smaller than 10%, 26.03% present an error comprised between 10 and 20%, 17.81% an error between 20 and 30%, 12.32% an error between 30 and 40%, and 4.11% an error between 40 and 50%. Less satisfactory results were only obtained in 6.85% of the locations (with an error between 50 and 100%), whereas errors in excess of 100% only occurred at 2 stations.

## 5. CONCLUSIONS

Modelling the atmospheric corrosion of carbon steel in a fragmented subtropical environment, presenting a wide variety of microclimates such as those found in the archipelago of the Canary Islands, faces major difficulties. Neither the double-logarithmic law, widely accepted in the modeling of atmospheric corrosion, or other models proposed for larger geographic areas with environmental conditions apparently close to those exiting in the Canary Islands, can provide satisfactory predictions for the corrosion rates of carbon steel.

To improve the modeling of atmospheric corrosion, qualitative variables accounting for the major differences in corrosion aggressiveness between close locations were introduced in the mathematical equations. They were defined from a classification of the locations according to their corresponding index of corrosivity according to norm ISO 9223, though this norm does not adequately describe the atmospheric corrosion of a fragmented subtropical environment by itself. In this way, a major improvement of fit quality for corrosion rate prediction is achieved, though error ranges are still unacceptably big.

Further improvement was achieved by allowing variable levels of the pollutants $SO_2$ and chlorides and for the time of wetness in the mathematical model using observations during one year exposure. In this way, fitting errors in the prediction of corrosion rates for periods longer than one year were greatly diminished, as ca. 74% of the stations delivered absolute errors in the predicted corrosion rates below 30%.

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