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Atmospheric corrosion rates of copper, galvanized steel, carbon steel and aluminum in the metropolitan region of Salvador, BA, Northeast Brazil

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Abstract

The extension of the Brazilian coast contributes positively to the degradation of materials by the conditions of average temperature and relative humidity (RH%) much higher than in other regions, especially when looking at the coastal areas of Northern and Northeastern Brazil. Salvador is a city of hot and humid, typically tropical, with about 2,466 h annual sunshine, with annual winds speed average of 2.2 m/s, an average annual temperature of 25 °C and annual average RH% of about 81%. These weather conditions coupled with industrial pollution are extremely harmful, providing corrosion or degradation of metallic materials, by having a time of wet surface (t) high (4,000 h/year), in this case, classified by NBR 14643 as high corrosive environment, t_4. Based on this information it proposes investigate various aspects to determine the rate of corrosion and deterioration of metals used in electric power transmission and distribution lines (DL) in the metropolitan region of Salvador, Bahia, Brazil.

Keywords: Atmospheric corrosion; Metals degradation; Dose-response function.

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1. Introduction

The extension of the Brazilian coast contributes positively to the degradation of materials by the conditions of average temperature and relative humidity (RH%) much higher than in other regions, especially if one considers the coastal areas of Northern and Northeastern Brazil [1].

According to Köppen *apud* Portella *et al.* [1], Salvador, Bahia, is a tropically city having about 2,466 h of sunshine a year, annual winds with average speed of 2.2 m/s, an average annual temperature of 25 °C and annual RH% of 81. These climatic conditions coupled with a moist surface time (t) high (>4,000 h/year), and industrial pollution harmful to materials engineering, leading to corrosion or degradation of metallic materials, classified by NBR 14643/01 [2], standardization as t_4, or high corrosive environment (C_4) [2,3].

Thus, the study of variables that influence the process of atmospheric corrosion is of fundamental importance, given that most of the materials present in everyday life is susceptible to degradation. It has, for example, most metals of distribution and transmission power lines, as well as data communication, such as cables, towers, telephone lines, networking accessories, among others [3,4]. In this research was investigated various aspects to determine the rate of corrosion and deterioration of some metallic materials of overhead electrical power distribution (RD) of the Salvador metropolitan region, Bahia (SMR), Brazil. For this purpose, a methodology was developed based on the development of 8 atmospheric corrosion sites (ACS) in different environments where they were monitored monthly meteorological parameters and the deposition rates of major air pollutants (chloride and sulfate ions and particulate materials, measured by directional dust dispositive gauges (DDDGs)) in order to obtain subsidies for the classification of atmospheric corrosivity. In these ACS were installed modules beyond the collection of pollutants, natural weathering panels with metallic materials samples: carbon steel, galvanized steel, aluminum and copper into plates form and carbon steel cylindrical coupons.

1.1. Corrosion

The atmospheric corrosion is one of the most common corrosion processes, because the vast majority of structures exposed to the atmosphere are metallic. It occurs when forming a thin film of electrolyte on the metal surface, allowing the attack of the electrochemical type. The film is formed due to the presence of moisture in the atmosphere. Even for low RH% as 60% may develop that film [5]. The corrosion rate depends strongly on relative humidity and the constituents of the atmosphere [6].

The NBR 14643 [2] standards provides guidelines for the classification of corrosivity of the atmosphere compared to standard metallic materials such as carbon steel, aluminum, copper and zinc. This characterizes the atmospheric corrosivity in 5 categories, ranging from C_1 (very low) to C_5 (very high).

The degree of corrosiveness of the atmosphere over the zinc galvanized steel, carbon steel, aluminum and copper can be made from corrosion rates obtained in the first year of exposure, as shown in Table 1 [2].

Table 1.   Metal corrosion rates according to NBR 14643 [2].

Category	Units	Zinc	Copper	Aluminium	Carbon steel
C_1	g/m²/a	≤ 0.7	≤ 0.9	Negligible	≤10
	μm/a	≤ 0.1	≤ 0.1	negligible	≤ 1.3
C_2	g/m²/a	0.7 -5	0.9-5	≤ 0.6	10-200
	μm/a	0.1- 0.7	0.1-0.6	-	1.3-25
C_3	g/m²/a	5-15	5-12	0.6 - 2	200-400
	μm/a	0.7-2.1	0.6-1.3		25-50
C_4	g/m²/a	15-30	12-25	2-5	400-650
	μm/a	2.1-4.2	1.3-2.8	-	50-80
C_5	g/m²/a	30-60	25-50	5-10	650-1500
	μm/a	4.2-8.4	2.8-5.6	-	80-200

Note: the corrosion rates are expressed in grams per square metre year; and micrometres per year (Statistical treatment).

1.2. Dose-response function

The dose-response function is important for the development of classification systems for corrosive environments, for mapping areas at risk of corrosion and to calculate the cost of damage caused by the deterioration of materials.

The behavior of the phenomenon of atmospheric corrosion of metals is governed by the Pourbaix Eq. 1.

$$P=K.t^n \qquad (1)$$

Where: (D) represents the loss of thickness of the metal in [μm]; or weight loss (g); (t) is the exposure time in months or years; (K) and (n) are constants calculated by logarithmic linearization. The constant (K) represents the mass loss for the first year, and the constant (n) suggests the passivating effect of the environment, which depends directly on the metal, the physicochemical conditions of the atmosphere and exposure conditions. These constants are empirically determined by extrapolating bi-logarithmic experimental data of corrosion (μm) or (g) vs. time (months) according to Eq. 2.

$$log P= logK+ nlogt \qquad (2)$$

The representation in log-log coordinates of Equation (1) as shown by Equation (2) is a straight line. By linear fit using the least squares method obtains the constants K (Intercept) and n (inclination).

It is also possible to determine the constant K based on the content of pollutants (Cl an SO_2) and aerosols, particulate materials (PM) by means of linear fit which results in Eq. 3.

$$K'=a_0+a_1.[Cl^-]+a_2.[SO_2]+a_3.[PS] \qquad (3)$$

Where the coefficients (a_0 - a_3) are the calculated constants; (K') is the average annual mass loss in g; [Cl^-] is the average annual deposition rate of chlorides in [mg/m².day]; [SO_2] is the average annual total rate of sulfate in the atmosphere; and [PS] is the average annual levels of particulate materials in

[mg/m^2.30 days], or the conductivity of its aqueous solution, in [µS/cm].

With this treatment the obtained dose-response function which expresses the thickness loss or loss of average mass of metal exposed in each natural ACS as described in Eq. 4.

$$C = K'.t^n \qquad (4)$$

Where: (C) is the prediction of corrosion in [µm] for a certain period of time (t) in years or months. Equation (4) can still be differentiated to obtain the corrosion rate of spontaneous a function of time (t) in [µm/year], according to Eq. 5.

$$[dC/dt] = K'n.t^{(n-1)} \qquad (5)$$

1.3. Climatic Classification

The numerical value referred to as Brooks deterioration index (Id), may represent the corrosion potential from meteorological data and is calculated from the saturation pressure of steam (this value can be calculated experimentally or by using standard tables) [7] the temperature and RH% averages in the region.

In accordance with the Id value, the deterioration index is illustrated in Table 2.

Table 2.   Brooks deterioration index [8].

Id	Deterioration rate	Id	Aggressivity categories
Id < 1	Very low	0 -1	Not aggressive
1 < Id < 2	Low	1 - 2	Very low aggressive
2 < Id < 5	Moderate	2 - 4	Low aggressive
Id > 5	High	4 – 5	Aggressive
		5 -10	High aggressive

2. Experimental

For the classification of atmospheric corrosivity and the investigation of their effects on metallic materials (carbon steel, galvanized steel, copper and aluminum) were installed 7 ACSs located in different areas of SMR, BA, ranging from the aggressive environments, due to salinity and industrial pollutants, even the least aggressive in the most remote regions of these types of pollution sources. These ACSs were mounted in the power distribution substations (SE) places of the MRS, BA. The location of the ACSs, the exposure time of the test specimens to the atmosphere, as well as the respective distances of each ACSs from the seashore can be seen in Table 3.

Table 3.   ACSs installed in SMR, BA.

ACS		Exposition time		ACS distance from seashore (m)
		Start	End	
1	SE Cajazeiras (CJD)	9/24/2008	9/5/2009	2940
2	SE Complexo Industrial (CIU)	9/24/2008	9/5/2009	7040
3	SE Paripe (PPE)	9/24/2008	9/5/2009	1680
4	SE Pituba (PIT)	9/24/2008	9/4/2009	500
5	SE Sauípe (SPS)	9/24/2008	9/2/2009	2870
6	SE Camaçari (CMU)	9/24/2008	9/2/2009	20,500
7	SE Amaralina (AML)	9/24/2008	9/4/2009	150

2.1. Chloride ion determination

The determination of chloride content in the atmosphere was performed according to NBR 6211 [9], which prescribe the moist candle method for determination of inorganic chloride (Cl⁻) by means of volumetric analysis.

2.2. Sulfur dioxide determination

It was performed according to NBR 6921 [10], which prescribes the method for the gravimetric determination of total sulfur dioxide rate in the atmosphere, obtained by oxidation or adsorption to a surface reactive sulfur compounds such as SO_2, SO_3, H_2S and SO_4^{2-}.

2.3. Directional dust dispositive gauges (DDDGs)

The method for measuring the severity of pollution DDDG, has been successfully applied by researchers from the Nirro Research Institute (Iran) [11] and by researchers at ESKOM (South Africa) [12]. In this method four calibrators dust directed to each of the cardinal points were used to collect particulate matter present in atmospheric air (PM). The method is simple to use, low cost, and maintenance-free. Moreover, the direction of greater intensity of pollution can be detected [11].

Several studies have shown the correlation of the results of DDDG with traditional methods of determining the severity of pollution (PSDD and NSDD) [11, 12].

The DDDGs were been installed at the average height of 3 m above the ground on all ACSs.

2.4. Weathering Stations

The implementation of weathering station aimed to evaluate the aggressiveness of atmospheric contaminants, allied to local climatic conditions on the performance of metallic samples similar to metal structures used in the region. These stations were located in an area capable of representing the best possible assessment of the region in order to consider the environmental parameters involved, because according to the nature and concentration of contaminants an environment can be characterized as too aggressive for a given metal and less aggressive to another.

The metal samples were installed according to ABNT NBR 6209 [13]. They were properly cut,

degreased with solvent (acetone), prepared by chemical cleaning, were weighed and its area determined according to ABNT NBR 6210 [14]. After preparation of these samples, they were identified. The samples were taken on a quarterly basis. After each exposure time a previous visual inspection and photographic recording was performed. Afterward an adequate cleaning of corrosion products were done in accordance with the kind of standard material. In this study, we adopted firstly mechanical cleaning of the light weakly adherent corrosion products, using a brush bristle, and then proceeded to the cleaning chemistry involved in the removal of products generated by dissolving the reagents in chemicals suitable for each type of material, in accord of NBR 6210 [14] and ASTM G1-90 [15].

The final mass of each sample after removal of corrosion products was determined by the intersection of the lines corresponding to the removal of corrosion products and the base metal attack. Because of this mass loss is influenced by the exposed area and the exposure time, these variables were combined and expressed in a formula that determines the rate of corrosion as standard [15], as shown in Eq. 6.

$$Corrosion\ rate = \frac{K.M}{S.t.\rho} \tag{6}$$

Where (K) is a constant which determines the corrosion rate; (M) is the weight loss in [g] to the nearest 1 mg; (S) is the area of the specimen in cm^2 with an accuracy of 0.01 cm^2; (t) is the exposure time in [hours]; (ρ) is the specific mass in g/cm^3.

In Fig. 1 is displayed in numeric order: (1) collectors chloride (upper support) and rate of sulfate (bottom support); (2) panel containing the metal specimens subjected to natural weathering: aluminum, carbon steel, galvanized steel and copper; (3) the module to collect weather data; and (4) the collectors of PM (DDDGs), respectively.
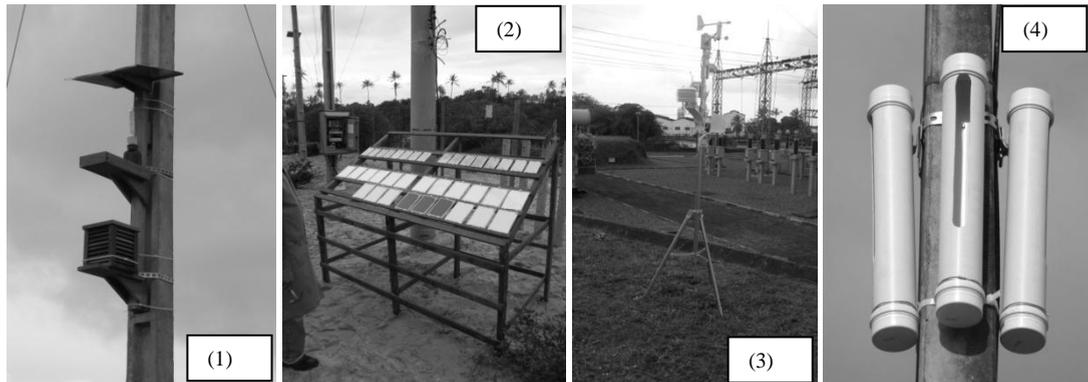

Fig. 1.   Pollutant collectors in the ACSs: (a) chloride (upper support) and sulfate (bottom), (2) the panel containing metals aluminum, carbon steel, galvanized steel and copper), (3) meteorological data equipment, and (4) DDDGs, respectively.

3. Results and Discussion

3.1. Meteorological data

In 2009, SMR, showed higher levels of rainfall to the latest annual averages [16, 17]. Thus, the rate of deterioration of the atmosphere (Id), obtained from Brooks expression was 5.1 to Salvador, Bahia, classified as very aggressive.

It was observed that the annual average temperature was about location (25.3 ± 1.2) °C [17]. According

Krab (1997) *apud* Kenny [18], the temperature exerts a dual role. If, on the one hand, its increase has a positive effect in raising the rates of reactions and ion mobility, their reduction may lead to condensation. It is assumed that an increase of 10 °C in temperature double the reaction rate, although there is evidence that this increase is only 1.6 times.

The climate of the city had a high RH%, which ranged from 74 to 98%, that leads to an increase of metal corrosion rate by forming a thin film electrolyte on the substrate. In turn, the precipitation (in Salvador had its maximum between March and September 2009) leads to the dissolution of ions from the atmosphere, mainly Cl^- and SO_4^{2-} from the sea. Moreover, the rain that is usually responsible for the leaching of pollutants, can also decrease the concentration of electrolytes and corrosion rate [18].

Aragão *et al.* [19] can be seen that the monthly averages reproduced the quarter found in the rainy climate of the region, from April to July, and April, the month of greatest variability and considerably above the average value.

The cumulative average solar radiation for the period of 2009 was about 2 MJ/m^2 [20], which in time brought direct influence of surface wet the metal and, consequently, the corrosion rate due to factors related to behavior of semiconductor oxides formed by corrosion products [4].

The average velocity of wind in the cumulative period of 2009 was approximately 7 m/s, with the predominant direction North or from the ocean. This parameter is related to the influence of the dispersion of air pollutants (salt spray [21]) and the drying time of the electrolyte on the metal surface. The highest averages of wind speeds in Salvador, in the period were recorded during March, April, July, August and December.

3.2. Chlorides

In Fig. 2, is shown the annual average concentration of chloride ion in both the rainy season (April to August), and the dry season (September to March). Leaching action of rain can reduce the corrosion attack due to the elimination or simply the dilution of chloride. However, it may be increase the conductivity of the electrolyte in any equipment parts, accelerating the corrosion process [4]. The results show during rain period that the concentration of chloride ion was higher, because of sporadic rainfall and higher wind speed.

According to Fig. 2 can also be observed that the ACSs PIT and AML stand out from the other stations by higher concentrations of sodium chloride. This is explained due to its proximity to the shoreline, when compared to other, a fact corroborated by other studies, such as Meira *et al.*, 2002 [22 - 25].

From these results, the aggressiveness of the environment for each ACS can be ordered as follows: AML> PIT> CJD> SPS > PPE, CMU> CIU.

In Fig. 3 are shown the average annual deposition rates of chlorides [mg/m^2.day] and the distances (m) from the seashore of each ACS installed in Salvador, BA, Brazil, in 2009.
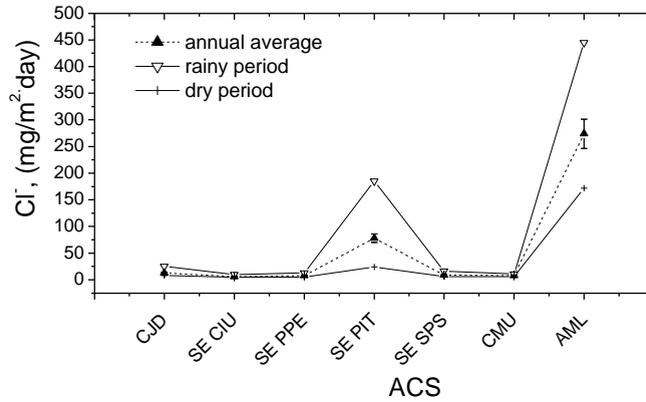
Fig. 2.   Annual average concentration of Cl⁻ [mg/m^2.day), during the rainy and dry period in the ACSs, in 2009.
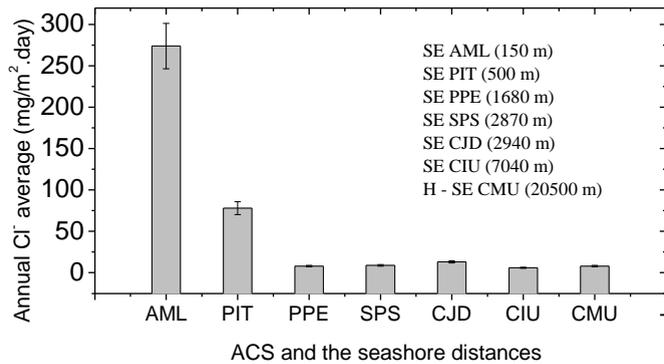

Fig. 3.   Average annual deposition rates of Cl⁻ [mg/m^2.day] x seashore ACSs distances (m), in 2009.

3.3. Sulfur dioxide concentration

The annual deposition rate of SO_2 for each ACS is presented in Fig. 4, along with their respective average values for the rainy and dry seasons. It was noted that the rate of precipitation did not exert great influences on the concentration of sulfur dioxide. Also, it was noted that CMU, CIU and AML, ACS´s had higher concentrations of SO_2 in relation to other stations, due to its proximity to the industries and seashore, respectively. On the basis of average values, the aggressiveness of the environment for each ACS could be ordered as: CIU> CMU> AML> PIT> CDJ> ≈ PPE SPS.
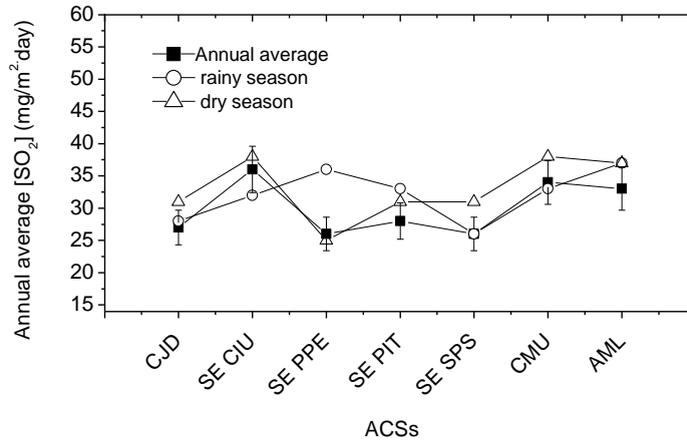
Fig. 4.   Annual average concentrations of SO$_2$ [mg/m^2.day], during rainy and dry seasons in the ACSs, in 2009.

From the results each ACS were classified as shown in Table 4.

Table 4.   ACSs classifications of corrosive categories, in 2009.

ACS	Corrosive categories
AML	Industrial marine
PIT	Marine
CJD	Rural
PPE	Rural
SPS	Rural
CMU	Urban
CIU	Urban

3.4. DDDG measurements

The conductivity of aqueous solutions from DDDG showed values lower than 150 µS/cm, except for ACS AML, whose value was (370 ± 37) µS/cm, because of its proximity to the sea line. The importance of this parameter is not only related to the concentration of particulate matter, but also to their shape and chemical composition. Solid particles in powder form of soot are responsible for increased atmospheric corrosion due to their hygroscopic properties, as amorphous silica. Gentil (2003) [26] mentions that it is indeed observed with metal particles such as iron and aluminum, which may increase the corrosion process when their chemical nature is different from the metal base (galvanic corrosion process).

From DDDG results the aggressiveness of the environment for each ACS could be classified as: AML> PIT> CMU≈CJD> CIU> PPE> SPS. The rainfall had no major influence on rates of atmospheric deposition of sediments. The results from DDDG's for each ACS shown that it were low aggressive, except for ACS AML who had an medium rating of aggression.

All results obtained might be explain the high corrosion rates of the distribution lines metals in the SMR, BA, Brazil.

3.5. Natural Weathering Stations

In Table 5, are presented the corrosion rates of carbon steel, aluminum, galvanized steel and copper. ACSs AML and PIT presented the higher rates of corrosion. As previously mentioned this fact is a consequence of its vicinity to the coastline and, in turn, caused by chemical attack by chloride ions. Analyzing the degradation of each metal separately, it was noted that carbon steel presented highest rates of corrosion. The copper and aluminum metals were better performance to atmospheric corrosion.

According to Table 5 was also possible to classify the ACSs corrosion regions on the analysis of Bahia from the 2009. For aluminum, the environmental aggressiveness was very high [8]. The chloride ions in the material caused the formation of pits. Another important observation was that its initial corrosion rate was more intense as a result of pre-treatment of material in the laboratory for removal of surface oxides adhered in order to standardize the results with other metallic materials worked.

The ACSs were classified into categories of aggression ranging from medium to very high, especially for ACS AML, which was high to very high aggressive by their proximity to the seafront. In this ACS was observed pits in aluminum samples measured from 13 to 39 μm depths, in the first year of exposure (Fig. 5). Its effect on the power line distribution cables, as an example, was determined mathematically. Their life span at the ACS location is around 30 years. However, real materials exposition demonstrates that its useful life is lower than that by the pits occurrence in all cable directions.

In Fig. 6, is shown an example of a geo-referenced map of the SMR, BA, Brazil, with respect to the corrosion rate of carbon steel (g/m^2.a).

Table 5.   Corrosion rates, exposure time, weight loss and atmospheric corrosivity category for carbon steel, aluminium, galvanized steel exposed on each ACS, in 2009.

ACS	Code	Annual average corrosion rates [g/m^2.a]	Annual average loss mass (g)	Loss mass [g] (year)	Corrosivity categories
CJD	A	15	0.21	0.25	C_{5+}
	C	240	4.22	6.76	C_3
	G	20	0.32	0.38	C_4
	CB	11	0.16	0.20	C_3
CIU	A	15	0.21	0.24	C_{5+}
	C	588	9.40	12.75	C_4
	G	16	0.28	0.40	C_4
	CB	30	0.44	0.51	C_5
PPE	A	13	0.17	0.23	C_{5+}
	C	243	4.58	8.09	C_3
	G	16	0.26	0.33	C_4
	CB	7	0.10	0.12	C_3
PIT	A	15	0.25	0.23	C_{5+}
	C	352	5.24	6.39	C_3
	G	22	0.39	0.53	C_4
	CB	41	0.56	0.65	C_5
SPS	A	15	0.31	0.17	C_{5+}
	C	272	4.90	7.80	C_3
	G	19	0.36	0.51	C_4
	CB	13	0.19	0.20	C_4
CMU	A	15	0.20	0.24	C_{5+}
	C	470	8.14	13.45	C_4
	G	14	0.22	0.27	C_3
	CB	9	0.13	0.18	C_3
AML	A	17	0.23	0.30	C_{5+}
	C	633	9.36	12.60	C_4
	G	58	0.52	0.17	C_5
	CB	75	1.00	1.13	C_{5+}

Note: A (aluminum), C (carbon steel), G (galvanized steel) and CB (copper).
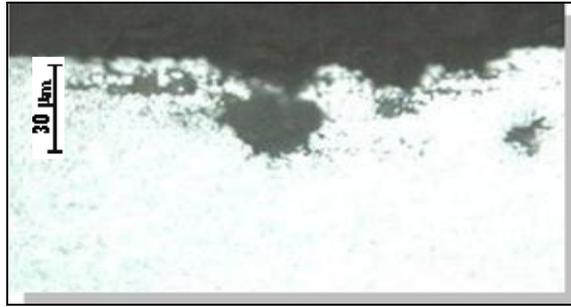
Fig. 5.   Optical microscope image from aluminum pit depth after 1 year exposition at ACS AML.
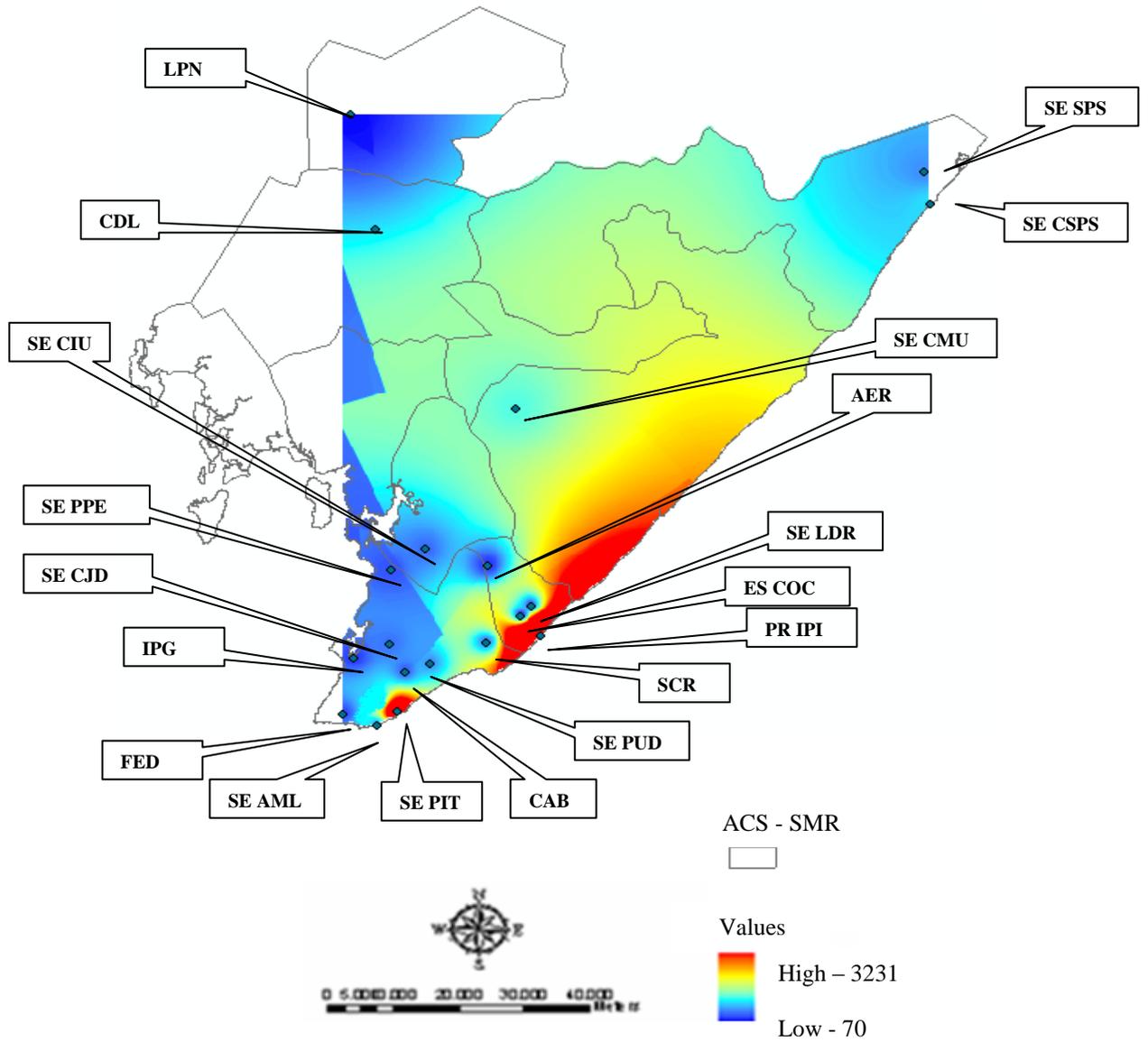
Fig. 6.   Schematically map of annual average corrosion rate (g/m^2.a) of carbon steel coupons installed in SMR, BA, Brazil.

4. Conclusion

The ACS located at maximum 500 m from the seashore distances as AML (150 m) and PIT (500 m) were greatest corrosion rates compared to other stations and, consequently, higher levels of chloride ions (typically marine environments).

Carbon steel presented higher rates of corrosion (240-630 g/m^2.a) compared to other metals.

Copper and aluminum metals were better performance against atmospheric corrosion, the corrosion rate close to maximum 80 g/m^2.a (copper) to 20 g/m^2.a (aluminum). In the aluminum samples exposed at 150 m from seashore presented pites on the order of 50 μm for the first year of exposition.

All ACSs analyzed were classified into categories of medium aggressivity (C_3) to very high aggressivity (C_{5+}), as ACS AML located at 150 m from the coastline. It was classified as a marine ambient.

Considering the concentrations of all pollutants analyzed, with an average annual temperature around 25 ºC, RH% of 81% and a t_4> 4,000 h/year, were the main factors for the high corrosion observed in ACS installed in SMR, BA, Brazil.

The highest rates of atmospheric deposition of chlorides were recorded precisely in the rainy season (April-August), the fact that in this period, rains were sparse and were in force winds with higher velocity (therefore a greater tendency to drag the particle long distances).

Regarding the presence of other contaminants, it was observed that for ACS CMU, located in the industrial complex and AML (150 m from the seashore) levels of sulfates were more significant, however, still considered low in relation to the rate of chloride as contaminants in atmospheric corrosion.

During the period, the Id of the SMR, BA, Brazil, was 5.1, classified as very aggressive.

The average annual temperature of Salvador, Bahia was about (25 ± 1) °C with high RH%, which ranged from 74-98%.

The climate in the period was characterized in two well defined seasons: the dry season, from August to March; and rainfall, April to July and is classified by Köppen methodology as hot and humid climate is typically tropical.

The cumulative average wind speed in 2009 was about 7 m/s, with the prevailing Northwest, or coming from the ocean. It corroborates the transport of chloride ions to the continent.

These data can be used in the ACS studies since it works with the same metallic materials and environmental conditions similar to the period analyzed.

Acknowledgements

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