



Tropical atmospheric corrosion of galvanized steel, in a light urban atmosphere in the San José valley of Costa Rica

Corrosión atmosférica tropical de hierro galvanizado en una atmósfera urbana leve, en el valle de San José de Costa Rica

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Abstract

Costa Rica imports most of the metallic materials it uses. In construction, Galvanized Steel (GS) is one of the most used elements in urban areas, where atmospheric corrosion is the main problem of its environmental deterioration. The area of greatest population and economic activity in Costa Rica is the San José Valley, which has a tropical monsoon climate with low pollution, defined under ISO 9223 as light urban. The present study of the atmospheric corrosion of the GS, proposes a high correlation for simple linear models, with climatic parameters as main components and SO₂ as secondary component. Seasonality and sampling sites are partially significant at the beginning of the oxidation process, but this effect is damped over time. The average corrosion rate after 2 years is in the order of 0.4 μm y⁻¹, which represents a low level (C2 according to ISO 9223). Complex annual corrosion models, such as those indicated by ISO 9223, overestimate the real corrosion value.

Keywords: atmospheric corrosion, galvanized steel, mathematical modelling, monsoonal climate, air pollutants, rain, time of wetness.

Resumen

Costa Rica es un importador de la mayoría de los materiales metálicos que utiliza. En la construcción el Hierro Galvanizado (HG) es uno de los elementos de mayor uso en áreas urbanas, donde la corrosión atmosférica es el principal problema de su deterioro ambiental. El área de mayor población y actividad económica en Costa Rica es el Valle de San José, el cual tiene un clima tropical monzónico de baja contaminación, definido bajo la norma ISO 9223(2012) como urbano leve. El presente estudio de la corrosión atmosférica del HG, plantea una alta correlación para modelos lineales simples, con parámetros climáticos como principales componentes y SO₂ como componente secundario. La estacionalidad y los sitios de muestreo son parcialmente significativos al inicio del proceso de oxidación, pero dicho efecto se amortigua con el tiempo. La velocidad de corrosión media luego de 2 años es del orden de 0.4 μm año⁻¹, lo que representa un nivel bajo (C2 según la norma ISO 9223). Los modelos complejos de corrosión anual como los indicados por la norma ISO 9223, sobrestiman el valor de corrosión real.

Palabras clave: Corrosión atmosférica, acero galvanizado, modelos matemáticos, clima monzónico, contaminantes del aire, lluvia, tiempo de humectación.

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1 Introduction

Galvanized steel (GS) is one of the most widely used materials in Costa Rica for construction, especially for roofing and drainage (Apuy, 2016). Atmospheric corrosion is one of the main problems for the definition of durability for these materials (NACE International Impact, 2016). The Costa Rican standard INTE C405 (2019) sets out the basic levels of alloy coating thicknesses on steel sheets, being a basis for the production of GS and similar or associated products. The current minimum value is 150 g m^{-2} of zinc, considering both sides.

The central area of Costa Rica, and in particular the San José Valley (SJV), concentrates most of the country's population and economic activity (PRUGAM, 2009; INEC, 2011; Estado de la Nación, 2014). The SJV is a mountain valley surrounded by the volcanic mountain range to the NE and by the Talamanca mountain range to the SW. It has a tropical monsoon climate, with a dry season from December to April and a rainy season from May to November with an average of $2\,300 \text{ mm m}^{-2}$ of rainfall. The climate presents slight variations depending on the altitude, with an average temperature of $20 \text{ }^\circ\text{C}$ and a relative humidity of 75 %, with main winds from the NE (Solano & Villalobos, 2000; Muñóz, *et al.*, 2002; IMN, 2008).

The levels of atmospheric pollution are low, so that the classification of the SJV according to ISO 9223 (2012) is of the light urban type. This makes the dependence of corrosion to a large extent associated with climatic parameters, with a corrosion level generally expected to be of the type C2 or C3 (Morcillo, *et al.*, 2012; Robles, 2013; Almeida, *et al.*, 2000; Neurohr, *et al.*, 2011).

Atmospheric corrosion of GS on a seasonal basis has not been studied for the SJV, with only a single reference in the MICAT project (Morcillo, *et al.*, 1998), with a value of $0.708 \text{ } \mu\text{m y}^{-1}$, but without establishing any kind of corrosion model. Subsequently, the PATINA Thematic Network (Morcillo, *et al.*, 2002) carried out a study for different Zn coatings, where the atmospheres like those of SJV, present corrosion levels between C2 and C3, with corrosion values somewhat higher than those presented by MICAT for Zn.

The prediction of atmospheric corrosion of Zn (or as GS) was initially approached with linear models, associated with atmospheric and pollution parameters.

Subsequently, depending on the availability of data, statistical methodologies of dose-response analysis and neural networks were considered. (Feliu, *et al.*, 1993; Morcillo, *et al.*, 1998; Mariaca, *et al.*, 1999; Díaz, *et al.*, 2003; Mikhailov, *et al.*, 2007; de la Fuente, *et al.*, 2007; Vera *et al.*, 2017; Yikun Cai, *et al.*, 2019) These methodologies allowed to establish general behavioural generalities for atmospheric corrosion depending on pollution levels, atmospheric parameters and the time considered. For low pollution atmospheres at short times, the dependence became more important on atmospheric parameters, which allowed a quick approximation with meteorological information only. This situation allows a quick visualization of the atmospheric corrosion of Zn in tropical areas with low pollution, as well as its adaptability to climate change. Due to this lack of information, it is proposed to evaluate the seasonal atmospheric corrosion of zinc from GS sheets at the SJV. This will also establish basic models of GS corrosion, as well as considerations for its protection and durability against atmospheric corrosion.

2 Methodology

The insert in Figure 1 shows the map of Costa Rica. The grey area in this map corresponds to the SJV. A detailed view of the valley is shown in the main frame of Figure 1, emphasizing the main urban areas, the topographical relief, the location of the weather and corrosion stations and the outline of the studied area. The position of the weather and corrosion stations were selected in function of the wind direction passing through the SJV (from the NE to the SW).

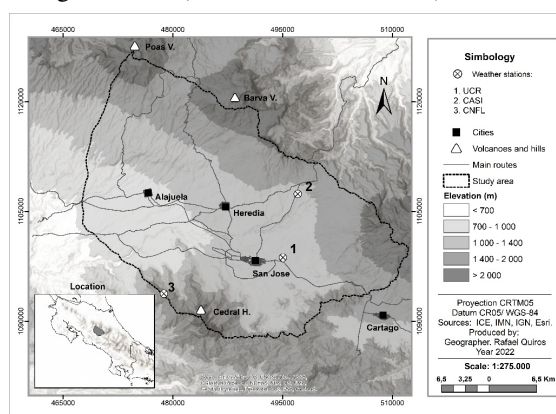


Figure 1.- The study area in San José Valley, Costa Rica.

2.1 Materials and parametric data

The galvanized steel (GS) used is produced in Costa Rica by immersion of a steel sheet in hot zinc, having more than 200 g m^{-2} of zinc, considering both sides. The gravimetric analysis according to ASTM A90/A90M (2013) indicates an average of 236 g m^{-2} of zinc. In proportion, the upper side had an average of $29 \mu\text{m}$ of zinc, while the lower side had an average of $12 \mu\text{m}$, measured by ultrasound, with a Kocour H-10M equipment. The GS sheet was 1.2 mm thick (18 gauge). GS is used with a minimum coating level of $10 \mu\text{m}$ on either side, to only have effects on Zn during the study period.

The GS samples were cut into 100 mm x 50 mm coupons. They were initially cleaned with soap and water to remove grease and dirt. Chemical cleaning was performed according to ASTM G1 (2013), method C 9.1. After, the sample is cleaned in an ultrasonic bath and rinsed with distilled water and acetone before dried in air. The edge of the coupons is coated with paint to prevent corrosion of the steel and to ensure that this process does not affect the corrosion level of the zinc. All the coupons were weighed and prepared for the exposure test (ASTM G50-20, 2020; ASTM G33 - 99(2020), 2020).

Corrosion monitoring stations were built based on ASTM G50-20 (2020) and ASTM G92-20 (2020) standards. Their installation sites are shown in Figure 1. CASI station is located at 1341 m.a.s.l.; UCR station, at 1210 m.a.s.l.; and CNFL, at 1772 m.a.s.l.

For the classification of corrosive atmospheres proposed by ISO 9223 (2012), climate parameters were evaluated based on meteorological data provided for stations near to the sampling sites by the Instituto Meteorológico Nacional (IMN). The parameters considered are Temperature (T), Relative Humidity (RH), precipitation (P) and wind (W). The time of wetness (TOW) is estimated according to the ISO 9223 (2012) counting the quantity of hours when the RH is higher or equal to 80 %.

Atmospheric pollutants were evaluated according to ISO 9225 (2012), using wet candles for chlorides (Cl^-) and passive monitoring such as Passam AG (2012), for sulfur dioxide (SO_2).

These methods are robust, low contamination and reliable in low pollution tropical environments. Vulcanological data on the dispersion of contaminants emitted by nearby volcanoes (Irazú, Turrialba and Poás), provided by public data from the Observatorio Vulcanológico y Sismológico de Costa Rica (OVSICORI) are also being analyzed in

relation to possible acid gases (HCl and SO_2), as well as particulate material. In similar way are considered the influence for tropical storms through the IMN, especially their influence on precipitation (OVSICORI, 2021).

Corrosion assessment of GS samples is performed using the gravimetric method of mass loss by chemical pickling according to ISO 8407 (2013), using the method C 9.1. Previously to the pickling the film of paint in the edges is removed with thinner.

Two series are exposed during a period of two years. The first series starts the corrosion process in rainy season (September 2018 to September 2020), and the second starts in the dry season (March 2019 to March 2021).

The samples of the 12 months were analyzed by Scanning Electronic Microscopy (SEM) and X-ray Diffraction (XRD), to characterize the sample in terms of corrosion products and their availability on the surface. The SEM microscope corresponds to a Carl Zeiss model Sigma 300 and the diffractometer corresponds a Bruker XDS model D8 Focus.

2.2 Corrosion models

The basic typical model proposed for atmospheric corrosion is that of a potential function whit time (Feliu, *et al.*, 1993; González, *et al.*, 2008; Garita, *et al.*, 2014; Morcillo, 2017), expressed as follows:

$$\text{Corr} = At^n \quad (1)$$

Where,

Corr = corrosion accumulated in the time, μm .

t = accumulated time, in years

Although this equation is heuristic, the principal interest in this type of equation is in the value of n which is inversely associated with the level of protection of the surface oxide. The same form, A constant is associated with the Corr of the corrosion in the first year.

Secondary are the lineal equations models (Roberge, *et al.*, 2002; Santana, *et al.*, 2003; Mikhailov, *et al.*, 2004; Ríos-Rojas, *et al.*, 2017), in their different variants (equations 2 to 4) according to:

$$\text{Corr} = a + b\text{Cl} + c\text{SO}_2 + d\text{TOW} + e\text{P} \quad (2)$$

$$\text{Corr} = a + b\text{LogCl} + c\text{LogSO}_2 + d\text{LogTOW} + e\text{LogP} \quad (3)$$

$$\text{logCorr} = a + n\text{logt} + b\text{Cl} + c\text{SO}_2 + d\text{TOW} + e\text{P} \quad (4)$$

where,

Corr = corrosion accumulated in the time, μm .

t = accumulated time, in years

SO₂ = accumulated SO₂ deposition, mg m^{-2}

Cl = accumulated Cl⁻ deposition, mg m^{-2}

TOW = accumulated time of whiteness, hours

P = accumulated precipitation, mm m^{-2}

This type of linear equations is widely used for a general interpretation of the influence of each parameter on atmospheric corrosion from small data sets.

Recently, the fusion of the different groups of corrosion studies (Mikhailov, *et al.*, 2004; Morcillo, *et al.*, 2012; Chico, *et al.*, 2017) present a general equation for estimating the annual value of corrosion for base metals, as a function of the annual levels of contamination and the climatic parameters of the studied site. These equations are included in the ISO 9223 (2012) and in the case of zinc, proposed equation has the form:

$$\begin{aligned} V_{corr} &= 0.0129P_d^{0.44} \exp(0.046RH + f_{St}) \\ &+ 0.0175S_d^{0.57} \exp(0.008RH + 0.085T) \quad (5) \\ f_{St} &= 0.038 \times (T - 10), \quad \text{if } T \leq 10 \\ f_{St} &= -0.071 \times (T - 10), \quad \text{if } T > 10 \\ N &= 114, \quad R^2 = 0.78 \end{aligned}$$

Note: N is the number of sites used for the equation (5), R² is the Pearson coefficient, f_{St} is a factor of steel, associate to the T effect.

Where,

V_{corr} = corrosion rate in the first year, $\mu\text{m y}^{-1}$

P_d = annual average SO₂ deposition, $\text{mg m}^{-2} \cdot \text{d}^{-1}$

S_d = annual average Cl⁻ deposition, $\text{mg m}^{-2} \cdot \text{d}^{-1}$

T = annual average temperature, °C

RH = annual average relative humidity, %

These models are evaluated in the different sites and seasons.

2.2.1 Control parameters of models

Before analyzing the models, a study of principal components and comparative tests between sites and time periods is carried out (Pearson factor correlations, Mann Whitney U, Kruskal Wallis) (Miller & Miller, 2002; Wilks, 2011). According to the results of these tests, specific considerations are made for equations 2 to 4, considering that they should have more data than variables to be modeled.

Three indicators of the level of error are taken as control parameters: Pearson's correlation coefficient

(R²), the sum of squared residuals (RSS) and Fisher's index (F). In them, it is taken as a consideration of a good adjustment that they must comply with R² > 0.7, RSS minimum and F > 100 (Miller & Miller, 2002; Díaz, *et al.*, 2003).

The statistical process was run in SPSS Statistical Analysis Software.

3 Results and discussion

3.1 Corrosion and associated parameters

The assessment of corrosion at the sampling sites and the meteorological and contamination data is shown in Tables 1 and 2, for starting processes in rainy and dry seasons respectively. The Table 3 shows the annual mean values of Cl⁻, SO₂, RH and T.

According to ISO 9223 (2012) the annual average values of Cl⁻ and SO₂ correspond to categories S1 and P0, respectively. These are indicated as low pollution values and therefore the SJV is considered as a light urban type of atmosphere.

The atmospheric parameters of T and RH are typical of tropical environments, with mean values of RH above 80 % and T above 17 °C, While the accumulated rainfall has a downward pattern in direction NE (Solano & Villalobos, 2000; IMN, 2008).

In accordance with the previous TOW values the ones shown here are high, being generally higher than 5000 hours (τ 5), with important effect in the Corr (ISO 9223:2012, 2012; Rodríguez Yáñez, *et al.*, 2015; Corvo, *et al.*, 1997, 2008).

The annual Corr values obtained in both seasons are associated with a category C2 (0.1 to 0.7 $\mu\text{m y}^{-1}$) according to ISO 9223 (2012), although with different final values, by season and site. These values are consistent with the general consideration of GS or zinc in rural or light urban atmospheres (Almeida, *et al.*, 2000; Morcillo, *et al.*, 2012; Restrepo, *et al.*, 2007).

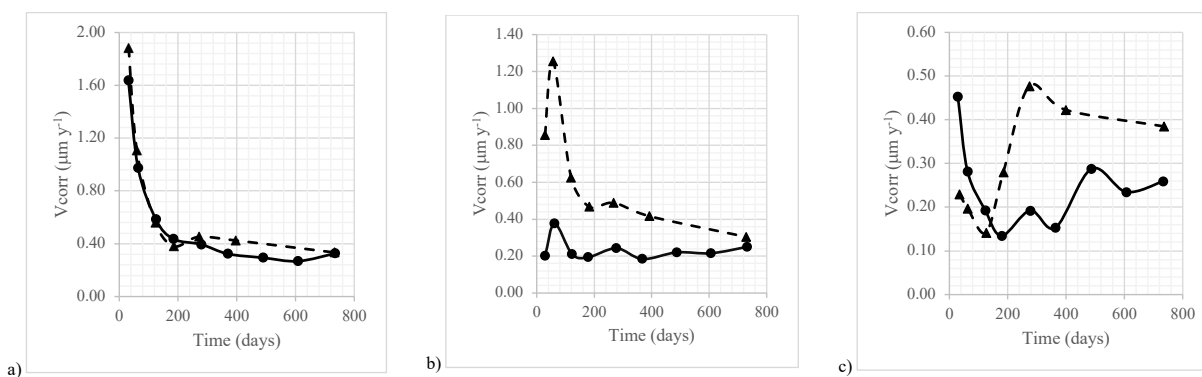
Alisios winds dominate the main wind component over the NE quadrant (Neurohr, *et al.*, 2011; Neurohr, *et al.*, 2013; Rodríguez-Yáñez & Chaves Villalobos, 2019).

3.2 Relationship between seasons

At all sites the general trend of Corr seems to indicate a lineal growth, while V_{corr} has an exponential decay. This can be seen in Figure 2, for all sites.

Table 1.- Corrosion data (Corr) and accumulated parameters for the first series (starting in rainy season).

Sites	Time (days)	Corr (μm)	P (mm m^{-2})	Cl ⁻ ($\text{mg}\cdot\text{m}^{-2}$)	SO ₂ ($\text{mg}\cdot\text{m}^{-2}$)	TOW (h)
UCR	29	0.016	305.4	109.29	199.06	540
	62	0.064	384.2	299.69	519.91	1054
	123	0.071	404	534.36	1659.25	1738
	179	0.095	404	819.56	2208.1	2272
	277	0.184	1077.2	1354.54	3157.23	3544
	368	0.186	1640.6	1408.7	3678.9	4992
	487	0.294	2211.6	1691.37	5204.95	6770
	606	0.358	2354.8	1926.04	6815.1	7984
	732	0.502	3619	2035.9	8348.36	10013
CASI	29	0.036	241.8	20.65	448.13	645
	62	0.048	294.4	26.81	667.84	1284
	123	0.065	354.3	174.75	2160.61	2489
	179	0.066	381.5	249.75	2637.83	3297
	277	0.146	717.8	658.49	3772.59	5147
	364	0.153	1113.3	1311.7	4906.55	7117
	487	0.384	1718.1	1870.71	6421.23	9803
	606	0.39	1827.5	2083.26	8221.96	12128
	732	0.52	2731	2443.93	11290.33	14830
CNFL	31	0.139	496.8	50.79	205.94	685
	64	0.171	573	56.32	456.26	1270
	125	0.2	591.6	498.99	1632.35	2058
	184	0.22	613.2	926.47	2404.61	2683
	279	0.302	1728.1	1314.47	3279.63	4168
	369	0.327	2205.4	1458.34	3916.48	5855
	489	0.394	3016.6	1854.26	5542.85	8042
	608	0.446	3259.3	2149.62	8667.44	9547
	734	0.657	4688.8	2437.85	10063.68	12008

Figure 2.- V_{corr} in both season: rainy (---●---) and dry (---▲---) in a) CNFL and b) UCR, c) CASI sites respectively

Corr is dependent on site characteristics but not so much on the onset season, while V_{corr} is affected by the onset season in the first months of corrosion.

The V_{corr} values tend to be in the order of 0.3 to $0.4 \mu\text{m y}^{-1}$. Being only the CNFL site the one with a linear trend in the relationship between V_{corr} in different seasons.

Table 2.- Corrosion data (Corr) and accumulated parameters for the second series (starting in dry season).

Sites	Time (days)	Corr (μm)	R (mm m^{-2})	Cl ⁻ ($\text{mg}\cdot\text{m}^{-2}$)	SO ₂ ($\text{mg}\cdot\text{m}^{-2}$)	TOW (h)
UCR	29	0.068	17.8	358.4	441	319
	57	0.196	244.8	418.47	853.13	769
	120	0.205	816	541.59	1081.68	1754
	183	0.234	1236.6	589.14	1470.8	2720
	268	0.359	1803.2	825.34	2748.25	4079
	393	0.448	1883.6	1083.68	3765.11	5328
	729	0.607	4103.6	1656.87	7750.28	10048
CASI	35	0.022	47.5	230.53	582.75	552
	63	0.034	190.5	344.88	1039.76	1145
	126	0.049	492.8	809.26	1480.71	2488
	185	0.142	728..7	1061..95	2268.73	3747
	274	0.358	1261.4	1611.88	3463.3	5686
	399	0.462	1402.1	1835.24	4630.04	8164
	735	0.775	2719.1	2475.43	9448.11	15336
CNFL	32	0.165	226.5	363.47	299.6	338
	60	0.182	622.2	413.73	639.01	870
	123	0.188	1203.7	466.36	968.51	2034
	185	0.193	1592.2	563.02	1511.86	3172
	271	0.336	2402..0	867.6	2839.86	4830
	396	0.461	2505.9	1239.56	4413.69	6414
	732	0.67	5373	2045.85	10450.29	12483

Table 3.- Annual mean values of Cl⁻, SO₂, RH and T, in each season.

Site	Cl ⁻ ($\text{mg m}^{-2} \text{ day}^{-1}$)		SO ₂ ($\text{mg m}^{-2} \text{ day}^{-1}$)		RH (%)		T (°C)	
	Rainy	Dry	Rainy	Dry	Rainy	Dry	Rainy	Dry
UCR	3.8	2.7	10	9.4	80.2	76.5	20.4	20.5
CASI	3.6	4.6	13.5	11.6	87.5	90.1	17.8	18.2
CNFL	3.9	3.1	10.6	11.2	84.4	83.9	17.6	17.6

The initial V_{corr} values in the rainy season increase when moving from the SW to NE of the valley (see Figure 2). The sites UCR and CASI are clearly affected for this effect. This is possibly because the decrease in the strength of the Alisios winds (from NE) brings moisture from the Pacific coast (from SW) that concentrates in the center and north side of the SJV due to the higher altitude of the volcanic mountain range (Muñoz, et al., 2002).

The relationship of the Corr in each season in the first year, is relatively linear (with the format Corr (dry) = a Corr (rainy) + b) and with different slope depending the site (see Table 4). The slope values are greater than 1, which would indicate that more corrosion occurs if the process starts in the dry season. This situation is especially important for the CASI site where the rainy season accelerates the corrosion

again. These sites have the highest SO₂ values, with a high TOW, with a moderate level of rainfall. This combination of factors, associated with a low level of initial corrosion, could lead to the loss of the protective corrosion products at the change of season, reactivating the surface.

Table 4.- Linear fit for the correlation between Corr dry vs Corr rainy for the first year (Corr (dry) = a Corr (rainy) + b).

Sites	a	b	R ²
CNFL	1.500	-0.0856	0.8676
UCR	1.895	0.0571	0.9492
CASI	3.6143	-0.1318	0.9552

3.3 Volcanic activity and tropical storms

The volcanic activity during the studied period was low, being mainly from the Turrialba volcano in eruptive emissions between September and December 2018, April and September 2019 and March to July 2020. Part of these emissions were directed to the SJV in November and December 2018 and April to May 2020 but did not have a significant influence in the global values. There were also slight emissions from Poás volcano between November and December 2018, but the main direction was towards areas west of the SJV (OVSICORI, 2021).

Tropical storms ETA and IOTA affected indirectly the SJV during November 2020 (IMN, 2021; NOAA, 2021).

3.4 SEM and DRX

XRD study of the plates at one year showed no specific crystalline structures. This may be because the average pH of the rain is of the order of 6 to 5, at which many of the corrosion products are dissolved (Rodríguez-Yáñez & Chaves Villalobos, 2019; Herrera Murillo, *et al.*, 2012).

The expected corrosion products are ZnO (zincite), which eventually hydrates and forms hydroxides (Zn(OH)₂) and Zn₅(CO₃)₂(OH)₆ (hydrozincite), established in small surface films with growth granules at points of dust or contaminant accumulation. Both products are soluble in slightly acidic media such as those present in the rain at the SJV (Almeida, *et al.*, 2000; de la Fuente, *et al.*, 2007; Leygraf & Wallinder, 2016).

SEM micrographs showed homogeneous corrosion but with an effect on the grain boundaries (see Figure 3).

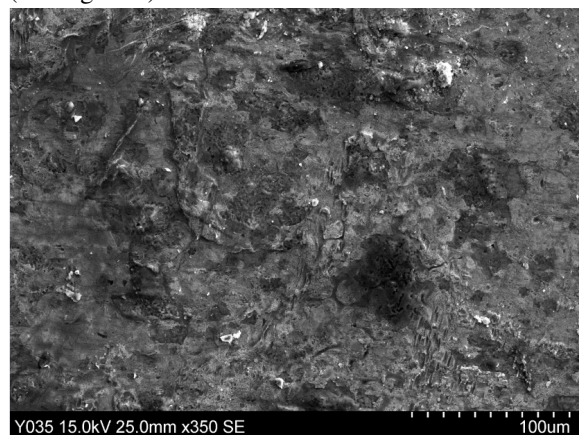


Figure 3.- GS surface in SEM, UCR site, month 12, rainy season series.

3.5 Data models

The models give the following values per site, per equation.

3.5.1 Corr vs, time model (equation 1)

Tables 5 and 6 show the correlations associated with equation 1 in the logarithmic form, for the stations in the different seasons for two years data, where Log Corr are the actual values obtained at each site associated with Log A.

All sites and all times show Pearson coefficients greater than 0.8, while the Log A values are different from Log Corr for one year at all sites and seasons.

Corrosion aggressiveness is linked to the inverse values of the constant n, which has site-dependent values. While at CNFL it is relatively independent of season, with values in the order of 0.45, at UCR and CASI their values are much higher (0.6 to 1.2) and dependent to the season. This difference is more important between stations when the corrosion starts in dry season. These values would indicate a partial protection for GS in CNFL, while for the UCR and CASI sites the protection would be minimal. This observation would be consistent with the fact that no protective corrosion products were found by XRD. The general equations by season are similar, so a simplified estimate of GS corrosion in the SJV could be generalized with the equation:

$$\text{LogCorr} = 0.7416\text{Log}t - 0.5214 \quad R^2 = 0.660 \quad (6)$$

The R² value in the equation 6, falls because there are significant differences between sites for the Log A and constant n values. Therefore, such a generalization is inappropriate.

Table 5.- Parameters of equation 1, in the rainy season.

Site	Log A	n	R ²	Log Corr
UCR	-0.6518	0.9609	0.9619	-0.7305
CASI	-0.6735	0.8604	0.8869	-0.8153
CNFL	-0.4454	0.4463	0.9152	-0.4855
General	-0.5902	0.7559	0.9213	

Table 6.- Parameters of equation 1, in the dry season.

Site	Log A	n	R ²	Log Corr
UCR	-0.3821	0.6141	0.9201	-0.3487
CASI	-0.4546	1.2902	0.9475	-0.3354
CNFL	-0.4078	0.455	0.8097	-0.3363
General	-0.4148	0.7864	0.8924	

Table 7.- Pearson correlation coefficient between variables.

	Corr (μm)	P (mm m^{-2})	Cl^- (mg m^{-2})	TOW (h)	SO_2 (mg m^{-2})
Corr	1	0.893	0.858	0.862	0.884
Rain		1	0.825	0.875	0.839
Cl^-			1	0.934	0.938
TOW				1	0.978
SO_2					1

3.5.2 Linear and logarithmic models (equation 2 to 4)

Pearson correlation coefficients for each parameter in relation to corrosion are calculated ($p > 0.01$) for two years. The values, with all parameters, are showed in the Table 7, and have a good correlation (more than 0.8) where SO_2 and P have the best correlations, followed in second order by TOW and Cl^- .

Comparisons between sites (Kruskal Wallis, $p > 0.05$) as well as the comparisons by season (U Mann Witney, $p > 0.05$) show no significant differences for two years. However, the same study for one year (less 400 days), mark differences between sites, especially for CASI and CNFL.

Since there is no significant difference by season, the modelling is considered globally by site and in the SJV, with different number of variables for two years.

The best results for equation 2 and 3, in its lineal and logarithmic forms, are:

$$\text{Corr} = 3.873E-2 + 9.788E-5P - 5.120E-5\text{SO}_2 + 5.392E-5\text{TOW} \quad (7)$$

$$R^2 = 0.8772, \quad \text{RSS} = 0.197, \quad F = 112.96$$

and

$$\text{Corr} = -0.8025 + 0.1471\text{LogSO}_2 + 0.1939\text{LogP} \quad (8)$$

$$R^2 = 0.6807, \quad \text{RSS} = 0.523, \quad F = 51.11$$

The most basic equations with minimum meteorological parameter are with TOW and P; expressed as a lineal regression (Restrepo, *et al.*, 2007; Corvo, *et al.*, 2008; Vera, *et al.*, 2017).

$$\text{Corr} = 4.655E-2 + 2.123E-5\text{TOW} + 7.707E-5\text{P} \quad (9)$$

$$R^2 = 0.8552, \quad \text{RSS} = 0.237, \quad F = 139.80$$

These equations show that the contribution of chloride (Cl^-) is not significant, possibly due to its low values. While P and TOW are presented as the main variables, followed by SO_2 .

For the equation 4, the Table 8 presents the coefficients for the equations with different number of variables for the SJV.

Equation 4 is a combination of Equation 1 and 2. It does not present a substantial improvement and increases the complexity, since it requires the measurement of more parameters.

The main variable in this system is time, which already presented a high correlation in equation 2, This factor is followed by P in a similar way as analyzed for equations 2 and 3.

3.5.3 Model ISO (equation 5) and Measured values

The values of equation 5 of ISO 9223 (2012) always present values higher than the measured values obtained for the SJV (see Table 9). This may be associated with the tropical conditions and low contamination levels in the SJV, which are a situation where the equation is not as adequate (Morcillo, *et al.*, 2012; Garita, *et al.*, 2014; Restrepo, *et al.*, 2007; Vera, *et al.*, 2017).

Table 8.- The best correlation obtained for the SJV, in general for the equation 4.

# variables	a	Log t n	P b	Cl^- c	SO_2 d	TOW e	R2	F	RSS
5	-1.82	3.51E-01	1.72E-04	2.21E-04	-1.45E-04	6.69E-05	0.722	25.447	1.957
4	-1.99	4.70E-01	1.69E-04		-1.28E-04	8.20E-05	0.712	30.007	2.079
3	-2.14	5.66E-01	1.47E-04		-2.67E-05		0.691	36.05	2.28
2	-1.98	4.74E-01	1.16E-04				0.691	53.525	2.333
1	-2.42	7.42E-01					0.652	88.963	2.687

Table 9.- Annual Vcorr values in ($\mu\text{m y}^{-1}$) according to the ISO 9223 (eq, 5), and Measured value obtained in each site.

Site	ISO 9223		Measure	
	Rainy	Dry	Rainy	Dry
UCR	1.0823	0.8784	0.186	0.448
CASI	1.6366	1.7402	0.153	0.462
CNFL	1.3649	1.3241	0.327	0.461

In low contaminated tropical atmospheres, such as that of the SJV, defined as rural or light urban by ISO 9223(2012), zinc (or GS) corrosion is mainly linked to environmental factors (Almeida, *et al.*, 2000). Of special attention in these cases are the wetting and drying cycles, as well as the averaged values of T, RH, TOW and the levels and intensity of rainfall (de la Fuente, *et al.*, 2007; Leygraf & Wallinder, 2016). Increasing T has a counteracting action, by increasing the reaction rate, but decreasing the effective evaporative wetting time, as well as the solubility of oxygen and other atmospheric gases. While the increment in RH (or TDH) increases the possibility of dew generation on the metal surface and with it the dissolution of the salts deposited on the surface. In contrast, rain generates a washing process of these salts, as well as some labile corrosion products, or the dragging of non-adherent ones, particularly in cases like this, where the pH is slightly acidic (Morcillo, *et al.*, 2012; Del Angell, *et al.*, 2015; Odnewall Wallinder & Leygraf, 2017; Graedel, 1989; Feliu, *et al.*, 1993).

Of particular importance is the level of SO₂ contamination in any type of atmosphere since a direct correlation between these and corrosion rate in zinc is proposed. Whereas, for Cl⁻, the correlation is clearer in marine environments, from S1 levels according to ISO 9223 (2102) (Morcillo, *et al.*, 2012). On the other hand, the particulate material deposited on the zinc surface favors oxidation by differential aeration, generating localized corrosion and/or accumulation points of oxidation products (de la Fuente, Castaño, & Morcillo, 2007). In this sense, the levels of PM in the SJV are low, so it is not considered as a parameter in the possible modelling (Herrera Murillo, *et al.*, 2012; Herrera, Rojas, *et al.*, 2014; Herrera-Murillo, *et al.*, 2020; DIGECA - MINAE, 2013).

In this sense, the values obtained for equation (1) show moderate to high correlations with time and medium to high n values. This is associated with the specific corrosion process of the zinc surface by charge transfer, but without the formation of a stable protective film that decreases the corrosion rate.

(Natesan, *et al.*, 2006; Morcillo, *et al.*, 1998).

There are high correlations between atmospheric and pollution parameters with corrosion of zinc. From this the linear models based on equations 2 to 4 correlate well with the main meteorological parameters mentioned for mild urban atmospheres, such as TDH and rainfall, as well as with SO₂, secondarily. The simplification to meteorological parameters for the linear equations (equation 9) maintains good correlation levels, avoiding the need to evaluate pollution, especially SO₂ (Restrepo, *et al.*, 2007; Santana, *et al.*, 2003; Corvo, *et al.*, 2008; Mikhailov, *et al.*, 2007; Yikun Cai, *et al.*, 2019; Castaño, *et al.*, 2007; Corvo, *et al.*, 1997; Mariaca, *et al.*, 1999; Rosales, 1997).

The approximation equation proposed by ISO 9223 (2012) is not suitable for estimation in tropical and/or low pollution atmospheres. This situation has already been expressed by other authors for zinc, as well as for other materials (Garita, *et al.*, 2014; Mikhailov, *et al.*, 2004; Chico, de la Fuente, *et al.*, 2017; Yikun Cai, *et al.*, 2019; Morcillo, 2017).

Conclusions

The SJV's atmosphere is dominated by its warm monsoon climate with seasonal rainfall and high RH that generates high TOW values. From this it is classified as mild urban C2 level, according to ISO 9223 (2012).

Initial corrosion growth is site dependent and to some extent dependent on the time of onset, but over 2-year average periods the sites and times become equivalent for the whole SJV, with an estimated average corrosion level of $0.4 \mu\text{m y}^{-1}$ (conservative).

The morphology of the attack is associated with a process of homogeneous surface zinc weathering, with some grain-edge damage, but no significant generation of corrosion products. This may be because they are mostly labile (soluble) in slightly acid rain (pH 6 to 5).

The models applicable to a global 2-year system show that the best approximation is of a linear

polynomial type (equation 7), without the effect of chlorides due to their low level in the SJV. The simplification with meteorological parameters is based on P and TOW (equation 9), while for the one-year analysis the simplified evaluations with time according to equation 1 can be site- and epoch-specific (see table 8 and 9),

The corrosion estimation model proposed by ISO 9223 (2012) is not applicable for tropical climates such as the SJV.

Based on the above, materials that comply with the INTECO C405 standard could have a long life, but this will also depend on the construction systems used, volcanic activity (especially SO₂ emissions), and the environmental effects of the site.

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