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Statistical Analysis of Factors Influencing Corrosion in Concrete Structures

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The use of mathematical and statistical models has allowed the description of the behavior of many natural phenomena. However, their application in civil engineering particularly, for the analysis of the corrosion behavior, has been overlooked in recent studies. In the present work, a factorial analysis with subdivided parcels design were conducted to evaluate the corrosion rate behavior of arrangements of protected and not protected steel bars found in reinforced concrete specimens subject to two different aggressive media. The results showed that, in comparison to sulphate ions, the effect of chloride ions on the corrosion rate was not statistically significant. In the same way, protected and not protected segments on the steel bars (i.e., steel bar condition) did not have a significant effect on the corrosion rate. The only factor found to significantly affect the corrosion rate was the variability of the beam fabrication process (i.e., beam factor).

Keywords: corrosion rate, reinforced concrete, statistical analysis, factor, effects

1. INTRODUCTION

It is widely recognized the observed useful life of concrete structures is generally shorter than that expected [1,2], and this situation has negatively affected the image of reinforced concrete as a long lasting material [3]. The durability of concrete structures depends on countless factors such as its design (water-cement ratio, steel proportion, quality of work) [4], materials used for its fabrication (cement, aggregates, water), fabrication procedures (wet curing time), and the environment under which it will serve (urban, marine, industrial or a combination). Degradation mechanisms and the type of attack observed on concrete structures depend directly on environmental parameters such as relative humidity, temperature, and wind speed and direction. The main sources of damage on concrete structures are: attack by sulphate, the frost and defrost, lime leaching, attack by acid substances, and the aging process [5].

Over the last year, several studies have looked at corrosion of reinforcement steel [6,7,8]. It is well known that elevated alkalinity in the concrete mixture chemically protects the embedded steel bar against corrosion. However, when the concentration of aggressive species on the steel bar surface exceeds a critical threshold value, this passive layer breaks down and active corrosion begins. As a result of the latter, the steel bar suffers a reduction in its adhesion to the concrete, its mechanical properties are downgraded, and byproducts of the corrosion process lead to an increment in volume of the bar. Such volume expansion produces tensile stress which eventually causes cracking and breaking off of the concrete cover [5]. This situation may be conducive to high risk conditions and potentially important economic losses. And can be prevented based on adequate inspection, evaluation and diagnosis of the corrosion process [9,10].

The use of evaluation techniques to quantify the corrosion rate has grown greatly in the last years. Specifically, several studies have focused on the development of new techniques to quantify the corrosion rate of reinforcement steel bars and in this way predict their residual life time [11,12,13]. The corrosion rate is commonly used to estimate the latter as well as evaluate overall structure damage; nonetheless, independently of the technique used, results have proven to be difficult to interpret especially under highly-fluctuating environmental conditions (i.e., fluctuations during initial stages prior to depassivation). In this sense, the use of statistical methods to infer relationships between electrochemical parameters associated to corrosion is fundamental. Nonetheless, the use of the former for this end has been generally overlooked [14]. In the present work, based on a statistical framework, we determined which conditions have the most influence on the corrosion rate of reinforcement steel bars in concrete beams when values are near the depassivation threshold.

2. EXPERIMENTAL PROCEDURE

2.1. Specimen fabrication

Two sets of six rectangular (200 mm x 200 mm x 800 mm) hydraulic concrete beams (n = 12) were fabricated, using for each one a 0.40 water/cement (a/c) ratio, compression resistance of 300 kg/cm^2 (ACI 318) [15], and four corrugated steel bars [16] as shown in Figure 1. Each concrete beam was divided into four (20cm long) segments, to obtain six different arrays combinations. The first array had the entire surface of the steel bars protected (all four segments), the second array did not have any of the four steel bars segments protected, and finally, the remaining four arrays had a combination of protected and not protected steel bar segments as shown in Figure 1. Protection was based on epoxy paint application in order to isolate the area from sources of corrosion. The wet curing time was 7 days in all cases.

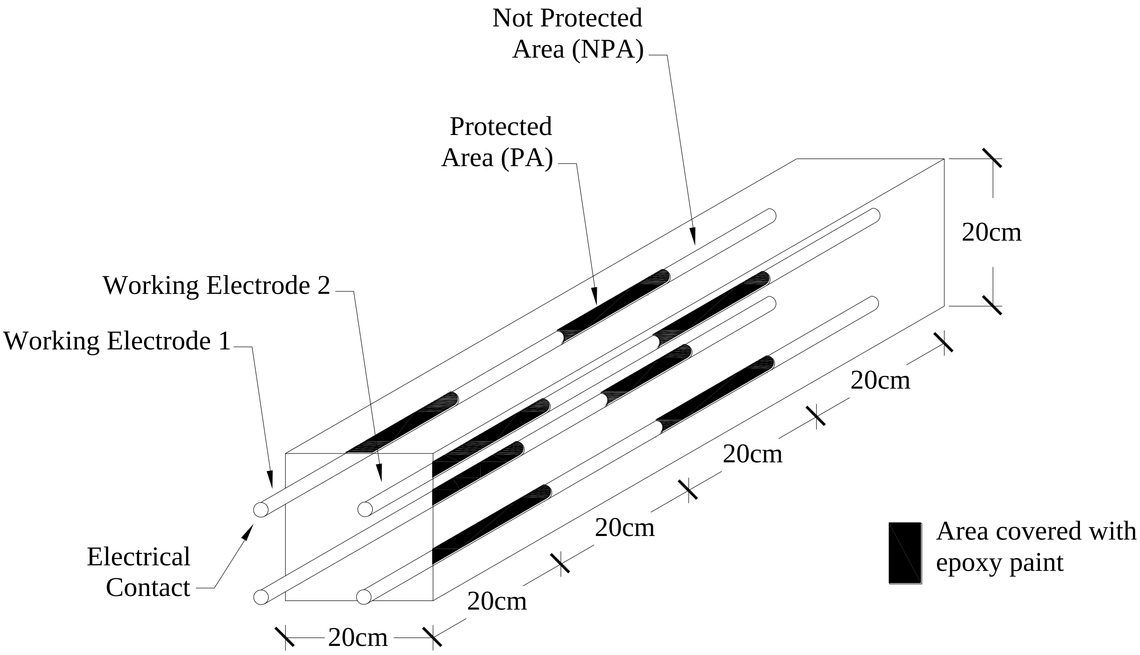

Figure 1. Sketch with the dimensions and characteristics of concrete beams.

Subsequent to the curing stage, one set of concrete beams was exposed to a sodium sulphate (Na_2SO_4) solution bath, and the other set to a sodium chloride (NaCl) solution bath. The solution concentration was 3.5% in both cases.

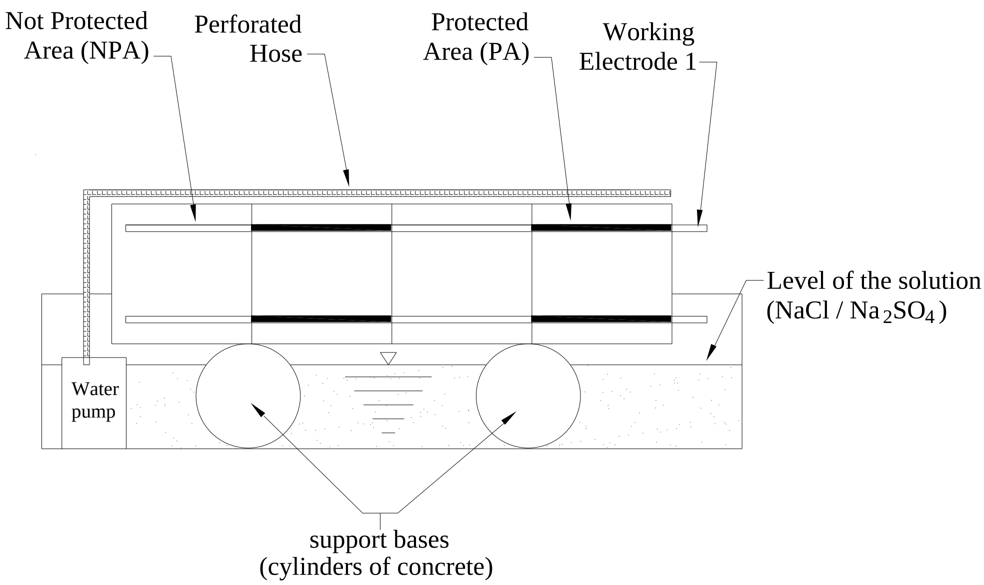

Figure 2. Side view of one of the concrete beams used for wet and dry cycles.

In order to implement the bathing cycles, a network of punctured hoses connected to a water pump was used. All hoses were covered with a cotton cloth to maintain homogeneous humidity level. Bath cycles consisted of 10 hours of wetting followed by 14 hours of drying, and this procedure was repeated throughout a 6-month period. Figure 3 shows a photo of the concrete beams immersed in the solution. Beams were mounted on two concrete cylinders as shown in Figure 2.

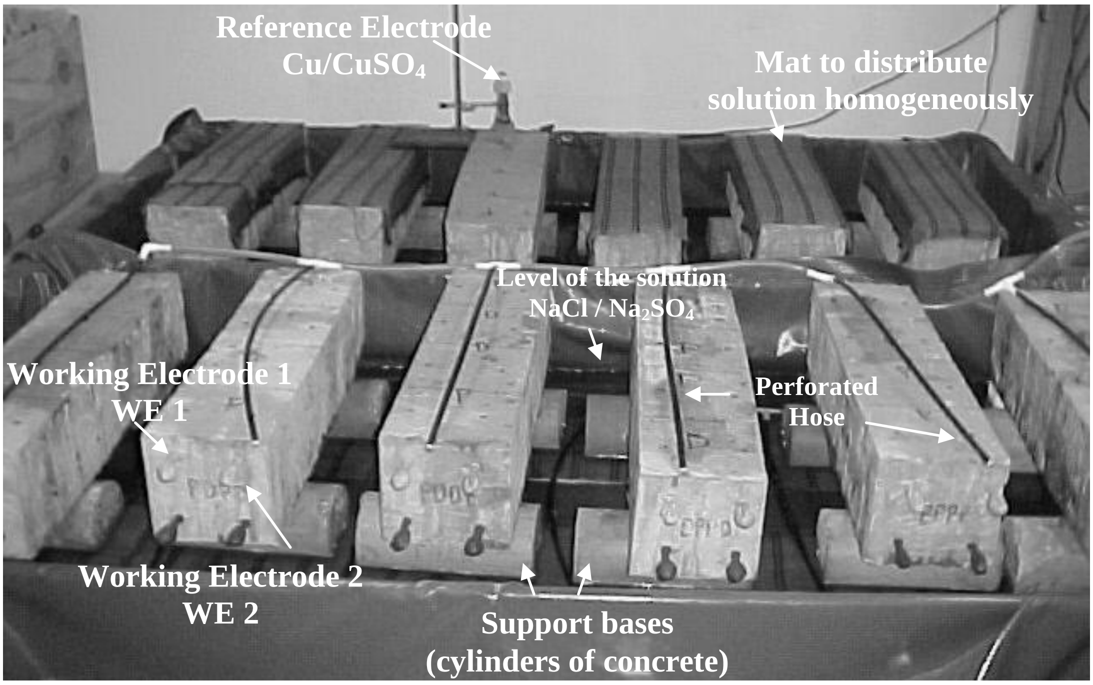

Figure 3. Concrete beams for experimentation

2.2. Electrochemical measurements

The corrosion rate (i_{corr}) was monitored based on the Electrochemical Noise Technique Electrochemical Noise (EN) measurements were performed with a commercial Potentiostat/Galvanostat/ZRA from ACM Instruments. Measurements were taken at the central portion of the each protected and not protected segment within each beam, as reported in [16].

The potential and current noise standard deviations were calculated from the ENMs. Based on the former it was possible to determine the noise resistance Rn (equivalent to the polarization resistance, Rp) as (Equation 1):

$$Rn = \frac{\sigma E}{\sigma i} \quad (1)$$

Where σE is the standard deviation of the potential noise and σi is the standard deviation of the current noise [17]. Using the Stern and Geary equation (Equation 2) it was possible to obtain the corrosion rate (i_{corr}) which is related to the corrosion intensity [18].

$$Rn = \frac{B}{i_{corr}} \quad ; \quad i_{corr} = \frac{B}{Rn} \qquad (2)$$

Where B is a constant (26 mV for fields measurements**),** Rn is expressed as ohm x cm^2 and i_{corr} as μA / cm^2.

2.3. Data

The corrosion rate was estimated for all twelve concrete beams. Measurements of each beam segment were performed approximately every 7 days for 6 months. The independent variables (factors) included in the statistical analyses were: treatment factor (ft), related to the use of sodium chloride or sodium sulphate solution cycles, bar condition factor (fc), related to protected or not protected segments on a beam (array), and the beam factor (fb), which was used to describe the variation that was due to the beam fabrication process.

2.4. Statistical analysis

Prior to the application of any statistical technique, it is necessary to conduct a descriptive analysis of the sampled data in order to identify its behavior and determine which statistical technique is most appropriate [19].

Once the previous had been done, a two-way analysis of variance (ANOVA) was performed to test for the effect of treatment (sodium chloride or sodium sulphate solutions) and effect of beam on the average corrosion rate values estimated for each beam. In addition, it was important to analyze the treatment effect together with the bar condition effect (protected or not protected), and beam factor effect. Thus, we also conducted a factorial analysis with a subdivided parcels design to analyze the combined effect (i.e., interaction) of treatment and bar condition on the average corrosion rate of the tested beams. The graphs presented in the results section were constructed using the statistical software MINITAB v.15.

3. RESULTS

3.1. Descriptive statistical analysis

The average i_{corr} values and their standard deviations for each concrete beam are presented in Table 1. Results show that beams 3, 4 and 8 had the largest standard deviations, which means that their estimated corrosion rate values are less reliable**.** Figure 4 shows the average i_{corr} values for each concrete beam. In this figure, the dashed lines on the i_{corr} axis represent the depassivation threshold (i_{corr} values lower than 0.1$\mu A/cm^2$ were in passivation zone and higher than 0.2$\mu A/cm^2$ were in active corrosion zone). The error bars represent the 95% confidence intervals (i.e., probability of 95% of finding the true corrosion rate value within the established interval), and are wider for beams 3 and 4, which is due to their larger standard deviations.

Table 1. Mean and Variance of i_{corr} for each of the concrete beams

Beams	Mean i_{corr} ($\mu A/cm^2$)	Standard deviation (i_{corr}, $\mu A/cm^2$)
1	0.17	0.21
2	0.12	0.17
3	0.23	0.36
4	0.21	0.36
5	0.15	0.20
6	0.13	0.20
7	0.23	0.26
8	0.22	0.29
9	0.11	0.12
10	0.21	0.24
11	0.21	0.23
12	0.18	0.20

Another important aspect during the initial statistical description of the data is to identify outliers that may become apparent only when the data values are separated into groups.

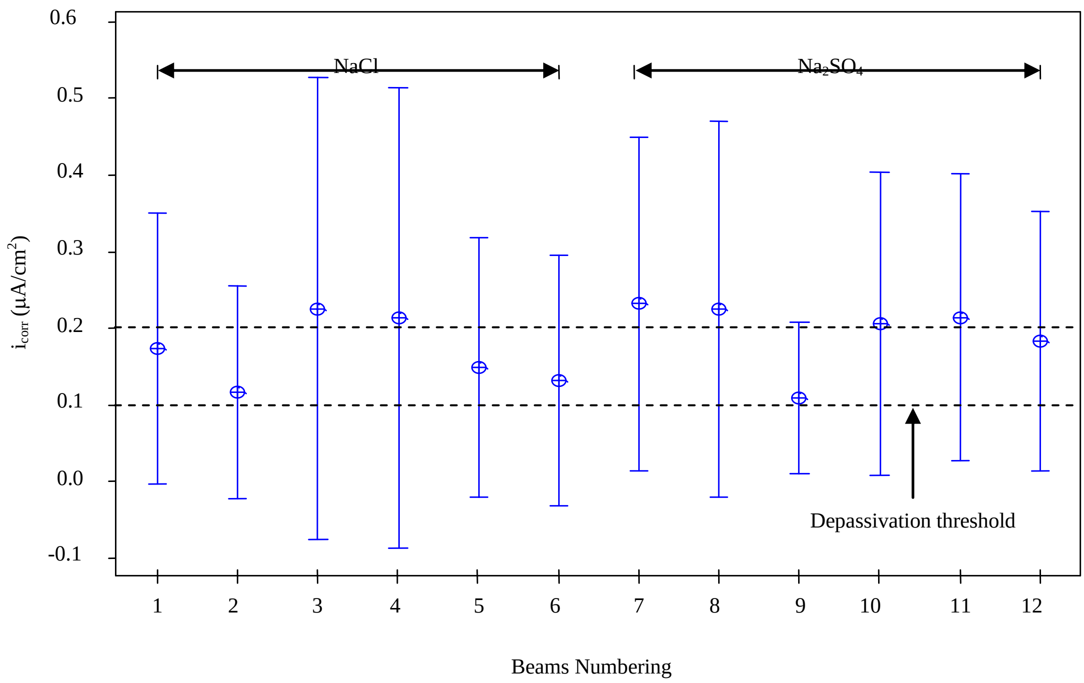

Figure 4. Intervals plot (95% of confiability) of i_{corr} presented for each beam

The most common method used for such end is box plots, which represent a graphical data distribution. The upper and lower boundaries of the box indicate the upper and lower quartiles of the distribution. Thus, the box length is the distance between the 25th percentile and the 75th percentile, and thus represents 50% of the data values located in the central portion of the distribution [20,21]. Box plots for the each concrete beam are shown in Figure 5. The point inside the box identifies the median of the i_{corr} values. The larger the box, the greater is the spread of the data. The lines extending from each box (called whist or) represent the distance to the smallest and largest observations that are less than one quartile away from the data contained in the box. Importantly, outliers are observations that range between 1.0 and 1.5 quartiles away from the box's limit. Figure 6 shows that beam 3, 4 and 8 had higher outlier's values which resulted in them having larger standard deviations as shown in Table 1. Likewise, such beams had the smallest confidence values of the entire data set.

In order to evaluate the relationship between i_{corr} behavior and treatment exposure time, box plots for each for concrete beams under each treatment level, those exposed to sodium chloride and those to sodium sulphate, are shown in Figures 6 and 7, respectively. Corrosion rate measurements were taken every 7 days, for 6 months.

The overall behavior of i_{corr} values of concrete beams exposed to the sodium chloride solution showed a high degree of dispersion during the initial period of treatment exposure which became progressively lower as the experiment progressed and reached its end (see Figure 6). In other words, data dispersion decreased as exposure time increased, which might be explained by the fact that during the final stage of the curing process the concrete pores suffered the greatest levels of humidity and the dissolved oxygen level increased the corrosion rate.

However, during the final stage of treatment exposure, the NaCl hydroscopic effect decreased the dissolved oxygen level (i.e., cathodic reaction) causing an increase in concrete porosity, and finally in the corrosion rate.

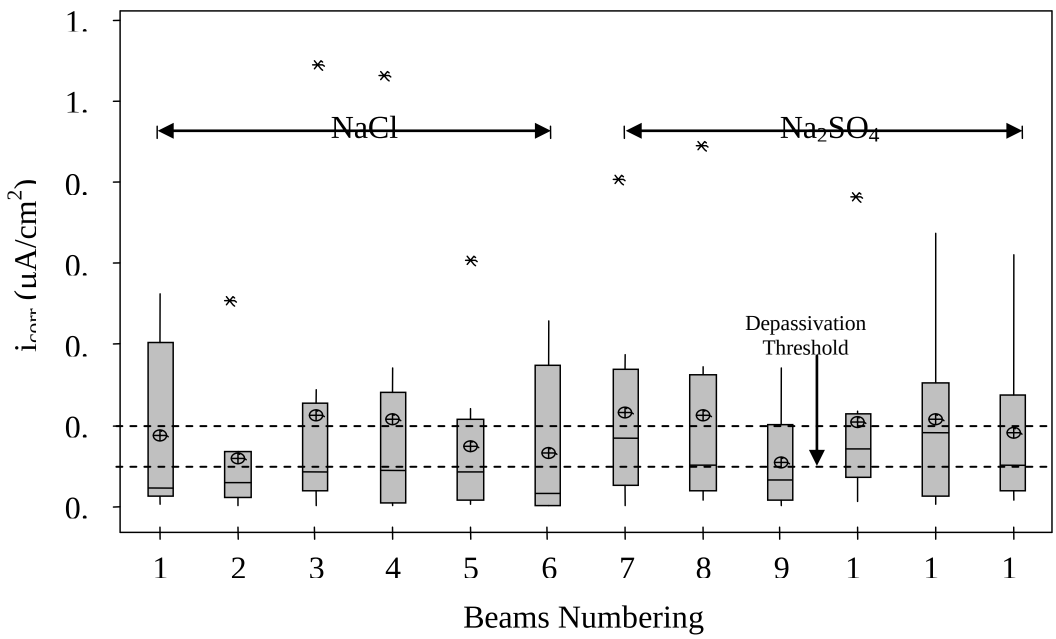

Figure 5. Box plot of i_{corr} for each beam

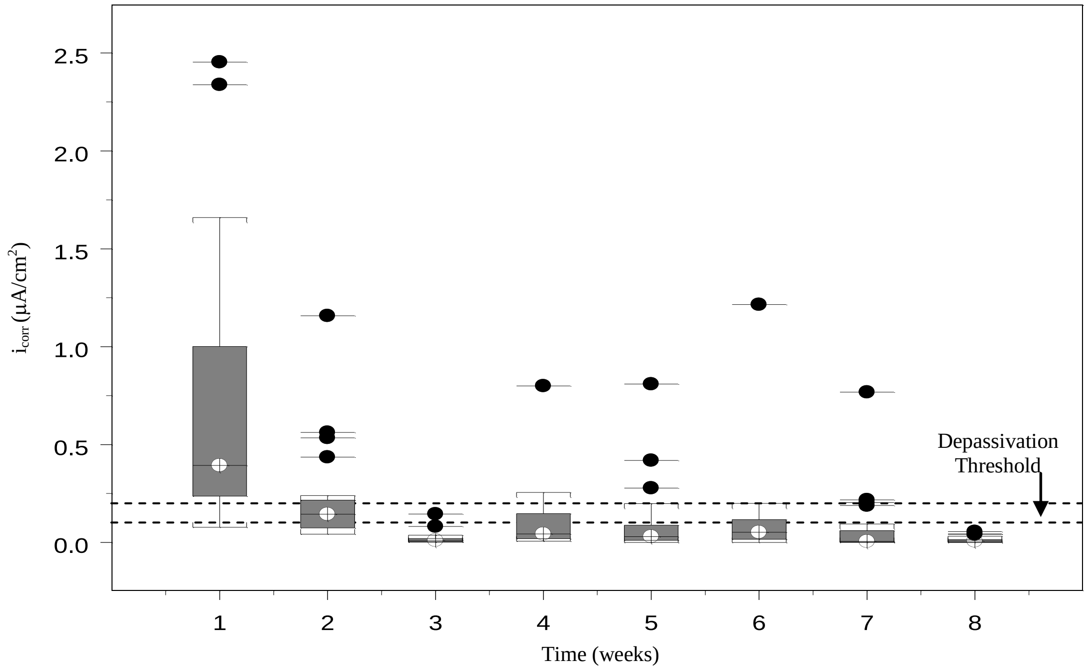

Figure 6. Box plot of i_{corr} of the beams exposed to NaCl

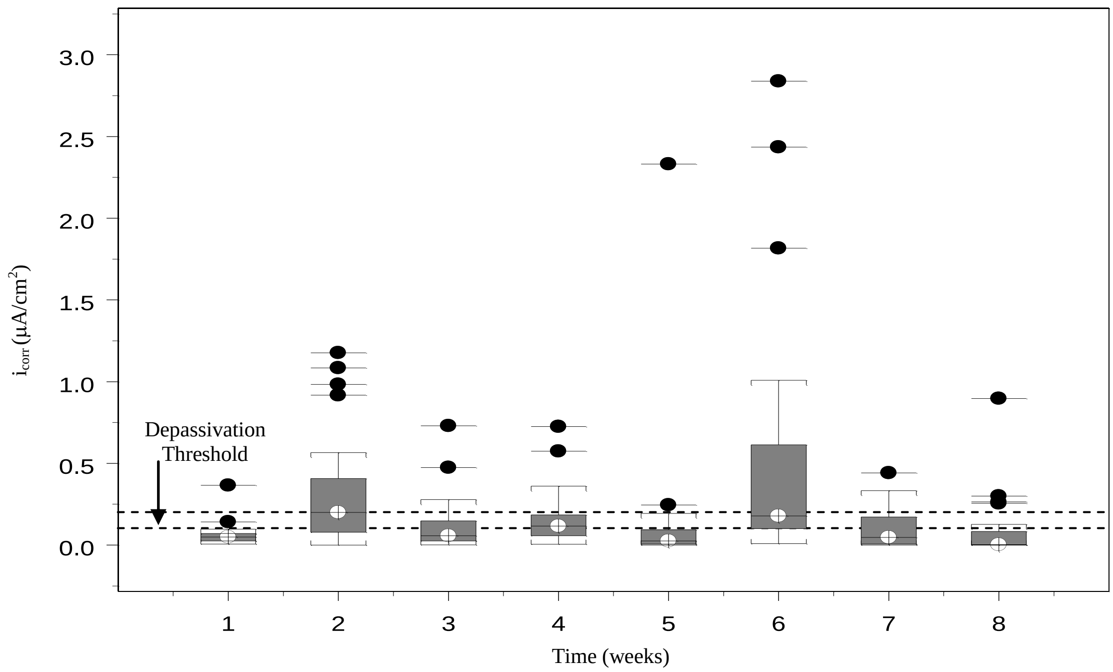

Figure 7. Box plot of i_{corr} of the beams exposed to Na_2SO_4.

In contrast, the overall behavior of i_{corr} values measured for concrete beams exposed to sodium sulfate showed a much lower dispersion during the first couple of weeks of exposure, which progressively increased until the end of the experiment (see Figure 7). This pattern may be due to an increase in sulphate attack rates on the concrete at the end of the exposure time period, which increased concrete porosity and finally, the corrosion rate.

The previously mentioned results from the descriptive analyses confirmed that the standard deviations of the calculated corrosion rate average values were never greater than three orders of magnitude, which allowed a more robust estimation of the corrosion rate behavior [22]. The following section describes the results from a two-way ANOVA used to test for the presence of a statistically significant treatment (sodium chloride or sodium sulphate solution exposure) on the and beam effects on the i_{corr} behavior.

3.2. Two-way Analysis of Variance with replicates (ANOVA).

Prior to conducting an ANOVA it is necessary to test for normality and homogeneity of variances of the observed data. To test for the former, a Shapiro-Wilk goodness-of-fit test was performed in order to validate if the sampled data statistically fail to describe a normal distribution [20]. The conclusion from such test is based on the General Decision Rule [19] using a p-value (i.e., probability of a result more extreme than that observed); see Table 2. Shapiro-Wilk test results showed p-values of 0.10 and 0.06 in the case of beams exposed to sodium chloride and sulphate solutions, respectively, and such result indicates that the sampled data have a normal distribution. On the other hand, to evaluate if the data showed homogeneity of, variances and F-test was conducted, which is used to validate if the samples or treatment groups present equal variances [20,21]. This test yielded a p-value of 0.94, which showed that the date met the assumption of homogeneity of variances. Meeting both assumptions justified the application of an ANOVA to evaluate the effect of the main factors on the corrosion rate.

Table 2. General rule of decision of the p value, for conclusion of Hypothesis Testing at a level confidence of 95%.

P Value	Decision
p values < 0.05	Ho is rejected
p values > 0.05 y <0.20	Uncertainty
p values > 0.20	Ho is not rejected

The main goal of the two-way ANOVA was to analyze if there was a statistically significant difference in i_{corr} values between concrete beams exposed to sodium chloride vs. those exposed to sodium sulphate, as well as the interaction between such treatment factors with the beam factor.

The ANOVA model used to evaluate such effects is defined below (equation 3). The beam factor (fb) had 6 levels (six different beams), while the treatment factor (ft) had 2 levels (sodium chloride or sulfate solutions). Together, these factors resulted in 12 different level combinations (iterations) [23].

$$X_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ijk} \quad (3)$$

Where:

X_{ijk} : i_{corr} measurements taken for each beam (data)

μ: population average of all beams in each treatment

α_i : main effect of beam factor (fb)

β_j : main effect of treatment factor (ft)

γ_{ij} : interaction term

The tested hypothesis is shown in Table 3. Results from the two-way ANOVA (with a 95% confidence level) are shown in Table 4. The observed p-value for the beam factor (fb) was 0.98 which confirms that the average corrosion rates were not statistically different among beams (see hypothesis in Table 3). In addition, the observed p-value for the treatment factor (ft) was 0.59 which means that the average corrosion rate values did not differ significantly between beams exposed to sodium chloride compared to those exposed to sulfate solutions (i.e., non-significant treatment effect). Finally, the interaction term was not significant either, as evidenced by a p value of 0.83 (see Table 4); in other words, the treatment effect was the same for all beams under study.

Table 3. Hypothesis to prove in the ANOVA in Two-way with replication.

Null Hypothesis	vs	Alternative Hypothesis
$H_{OA\mathit{ft}}$: $\gamma_{ij}=0$ for everything i,j	vs	$Ha_{\alpha\mathit{ft}}$: at least one γ_{ijk}K0
$H_{OA}: \alpha_1 = \ldots = \alpha_i = 0$	vs	Ha_{α}: at least one α_iK0
$H_{Oft}: \beta_1 = \ldots = \beta_j = 0$	vs	Ha_{ft}: at least one β_jK0

Table 4. ANOVA: Two Factor with replication of i_{corr} of exposed beams

Source of Variation	Sums of Squares (SS)	Degree freedom (df)	Mean Square MS	F statistic	p - Value	F critic
Beams Factor (fb)	0.035	5	0.007	0.11	0.98	2.32
Treatment Factor (ft)	0.016	1	0.016	0.27	0.59	3.95
Interaction	0.125	5	0.025	0.41	0.83	2.32
Error	5.082	84	0.060			
Total	5.260	95				

Although the results from the previous ANOVA did not show significant differences in corrosion rates due to treatment and beam factors, this test lacked the necessary sensitivity under conditions high within-group variation. On the other hand, this ANOVA did not test for interactions between the treatment, beam and bar condition factors all together. In order to evaluate the latter, a factorial analysis with a split plot design was performed. The statistical analysis of such design allows testing for each factor individually as well as their interaction, without affecting the global conclusions [21].

3.3. Factorial analysis with subdivided parcels.

Prior to conducting the factorial analysis we evaluated if the data met the assumptions of normality, homogeneity of variances and randomness. The design is represented in the arrangement shown in Table 5.

For this analysis we only used data collected from concrete beams that had combined arrays, that is, protected and not protected steel segments within the same bar (3&9, 4&10, 5&11 and 6&12).

Results from the factorial analysis showed non-significant treatment and bar condition effects on the corrosion rate (p-values of 0.967 and 0.897, respectively). The same held true for the interaction term. Figure 8 shows the corrosion rate behavior as a function of each factor (fb, ft y fc). The line with the smallest slope represents the least significant factor. Therefore, from this Figure it is clear that only the beam factor (fb) had a statistically significant effect on the corrosion rate behaviour. In other words, the beam fabrication or construction process had a greater effect on the corrosion rate of the beams than that observed for the treatment and bar condition factors. This result matched those observed from the initial descriptive analysis for which beams 3, 4 and 8 exhibited the greatest standard deviations and also show the largest outliers (see Figure 4 and 5). In addition, beams 6&12 had the slowest corrosion rates while beams 4&10 had the highest.

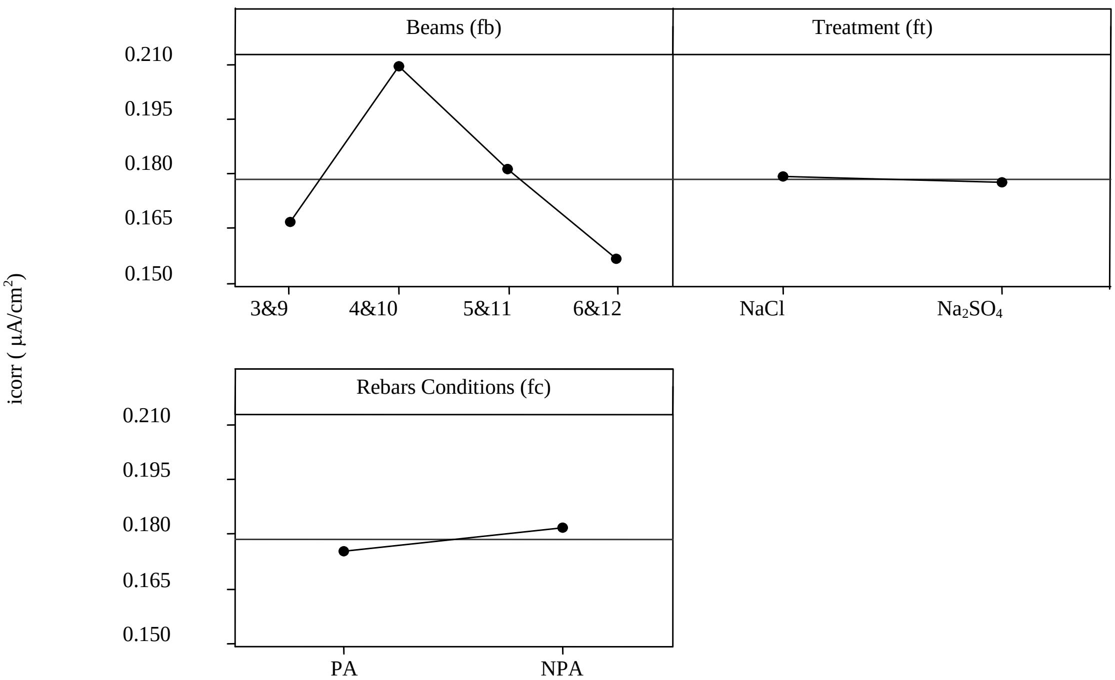

Figure 8. Main effects of the factorial design by subdivided parcels

Table 5. Scheme of the factorial design by subdivided parcels (y_{ijk}, i=1,..r j=1,...a k=1,..b).

Block: Beam 3			…	**Block: Beam 6**		
Condition Factor (fc)	Treatment Factor (ft)		…	Condition Factor (fc)	Treatment Factor (ft)	
	NaCl	NaSO4	…		NaCl	NaSO4
NP	y311	y321	…	NP	y611	y621
P	y312	y322	…	P	y612	y622
NP	y313	y323	…	NP	y613	y623
P	y314	y324	…	P	y614	y624

Where:
Treatment Factor (ft, NaCl, and Na_2SO_4)
Rebar Condition Factor (fc, Protected or Not Protected)
Block: beam 3, 4, 5, 6

Figure 9 shows the corrosion rate behavior of the studied beams as a function of the main factors (fb, ft and fc) and their interaction. Figure 9a and 9b shows the corrosion rate behavior of the beams (fb) as a function of different treatment solutions (ft) and bar initial condition (fc), respectively. Figure 9a shows that beams 4&10 exhibited a stable corrosion rate behavior under each treatment solution. However, beams 3&9 had higher i_{corr} values when exposed to sodium chloride relative to sodium sulphate, whereas beams 5&11 and 6&12 had higher i_{corr} values when exposed to sodium sulphate. On the other hand, Figure 10b shows that beams 3&9 and 6&12 had higher corrosion rate values when not protected, while beams 5&11 had comparable values when steel bars were protected. Finally, beams 4&10 had similar corrosion rate values for both protected and not protected steel bar segments.

Figure 9c and 10d shows the corrosion rate behaviour of beams treated with sodium and sulphate chloride (ft) as a function of the beam factor (fb) and the bar condition (fc), respectively. From Figure 10c it can be seen that beam 3 had a higher corrosion rate value when exposed to sodium chloride relative to beam 9 in sodium sulphate. Beams 4&10 had similar corrosion rate behaviors regardless of the treatment solutions while beams 5&11 and 6&12 had higher corrosion rate values when exposed to sodium sulphate relative to sodium chloride. Figure 10d shows that concrete beams treated with sodium chloride had higher corrosion rate values when the steel bars are protected, whereas beams treated in sodium sulphate experience the highest corrosion rates when the steel bars are not protected. Finally, Figure 10e and 10f shows the corrosion rate behaviour of protected and not protected steel bar segments (fc) as a function of the beam factor (fb) and each treatment solution (ft), respectively. From Figure 10e it can be seen that beams 3&9 and 4&10 had the same corrosion rate values regardless of bar condition (whether steel bars are protected or not). Beams 5&11 had a higher corrosion rate value when the steel bars are protected whereas beams 6&12 when the steel bars are not protected.

The corrosion rate behavior shown in Figure 9 confirms the importance of the beam factor in the observed results (i.e., variation due to beam construction is the most important evaluated factor affecting the corrosion rate).

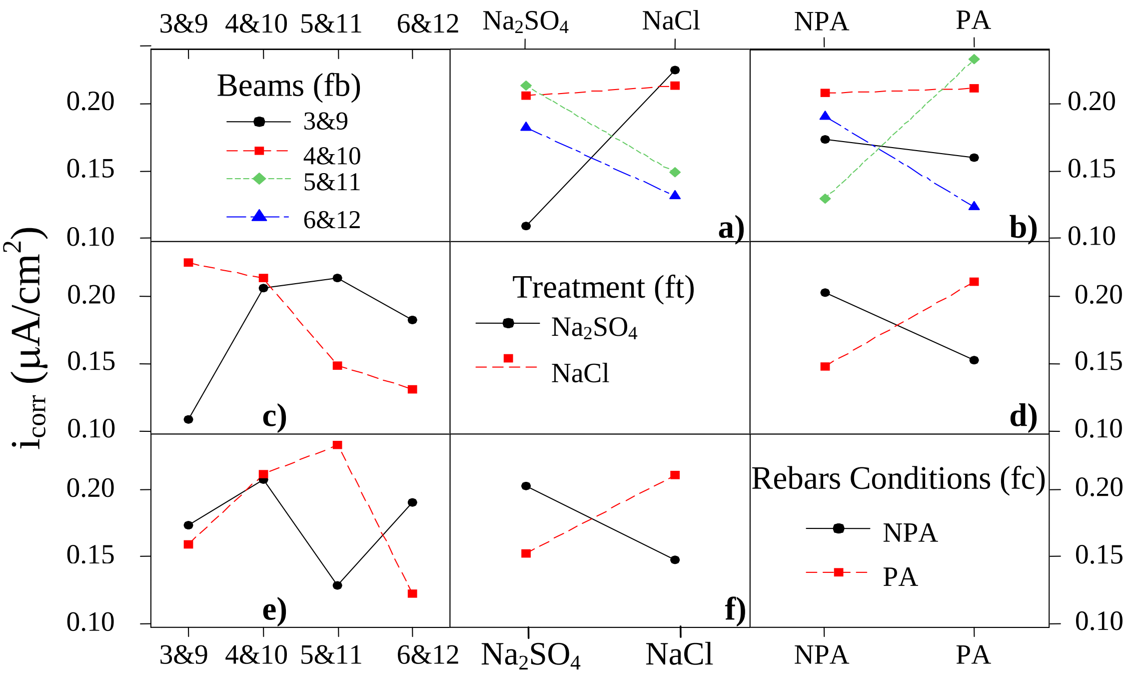

Figure 9. Interactions of the effects of the factorial design by subdivided parcels

4. DISCUSSION

The use of electrochemical techniques to measure corrosion rate behavior of steel bars in reinforced concrete, as well as the methods to determine corrosion rate values have been widely discussed in the literature [24,25,26,27]. Nonetheless, low corrosion rate values reported for passivation stages carry a certain degree of uncertainty due to the noise the measurement technique during this time interval. As a result, there have been no studies in the current literature that report a correlation between parameters and corrosion rate values during the passivation period.

Several recent studies have used statistical techniques to reduce the statistical error and in this way detect correlations hidden by the lack of sensitivity of electrochemical techniques [32,33]. Such statistical techniques, for example, have been used to estimate the service life period of reinforced concrete under submarine conditions as a function of concrete quality (diffusion coefficient), thickness, and environmental conditions [28]. Results from studies of this type have shown that (a) the service life period of reinforced concrete is more sensitive to the thickness of the concrete cover than to the diffusion coefficient, and (b) that the concrete is more sensitive to the superficial chloride concentration than to the critical chloride level [28]. An additional study reported results from a two-way analysis of variance which was used to study the compression resistance and elastic module of cylindrical concrete specimens with different additive materials (confinement) such as concrete paste, neoprene and sulphurous mortar. Results from this study showed that the different materials did not have a statistically significant effect on the response variables measured [29].

Other studies have focused on evaluating the performance of reinforced concrete structures by identifying which conditions affect the corrosion rate of the steel bars. Some of these have done so by using the area under the curve of the i_{corr} behaviour [30]. However, such investigations have not validity when the i_{corr} values are measured around the depassivation zone. It is in this sense that statistical techniques are of central importance in the analysis and diagnosis of corrosion rate data, as they help to reduce the statistical error, quantify the amount of variation in the data which is due to the main effects (factors) under study, as well as evaluate specific effects caused by external factors [31,32,33,34].

In this study, a two-way analysis of variance based on a factorial analysis with subdivided parcels was used to study the corrosion rate behavior of concrete beams with different arrangements of protected and not protected steel bar segments which were treated with two different aggressive media. The results showed that, in comparison to the effect of the sulphate ions, the effect of the chloride ions on the corrosion rate was not as statistically significant. In the same way, the steel bar condition (protected or not protected) had no significant influence on the corrosion rate although. Finally, the beam factor, i.e., variability in the production of the beams, was the only parameter which had a significant influence on the corrosion rate behavior. This latter result suggests that minuscule inconsistencies in the beam fabrication process which were previously thought to be insignificant can however produce a significant amount of variation in the corrosion rate of the steel bars, despite the fact that corrosion rate values are around the passivation zone.

4. CONCLUSIONS

The results reported in this study apply only to the specific set of conditions surrounding the conducted experiment, thus generalizations across different conditions must be made with caution.

The two-way analysis of variance based on a factorial analysis with subdivided parcels allowed evaluation of the effects of each factor, and in this way determine those which have a more significant effect on the corrosion rate. Results from this analysis showed that the most significant effect on the corrosion rate of the reinforced concrete beams was that the variability in the manufacturing process. In contrast, we did not find any statistically significant effect of either the bar condition (fc) or the aggressive media treatment (ft) on the corrosion rate.

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