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# Identifying Factors Influencing the Corrosion Rate of Steel Using Nonparametric Statistics

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Statistical techniques have made it possible to describe the behavior of certain phenomena. Nonetheless, given the difficulty in obtaining adequate data, it is common not to have random and homogeneous samples in order to conduct parametric statistical tests (which follow a known distribution). The present study reports results from the use of a non-parametric statistical test (which does not follow a known distribution) known as the Mood test of median differences which was conducted to analyze the corrosion rate of concrete beams exposed to different environmental conditions. The main objective was to statistically determine which factors accelerated the corrosion rate of the beams under study. Results showed that the tested factors (three different concrete covers: 15, 20 and 30 mm, and two water/cement ratios: 0.45 and 0.65), had statistically significant effects on the corrosion rate. Greater corrosion rates were observed for beams with covers of 15 and 20 mm, and with a water/cement ratio of 0.65. Nonetheless, we found that the corrosion rate was not statistically different between sides of the beam facing prevailing winds, and those that were sheltered from them.

**Keywords:** corrosion rate, reinforced concrete beams, non-parametric statistical techniques, factor effects

## 1. INTRODUCTION

Climatic conditions and other environmental factors have shown to greatly impact concrete infrastructure. Current changes in environmental conditions have influenced the durability of concrete structures and several cases around the World have reported [1,2], a decrease in the projected lifetime of such structures. Thus, the lack of maintenance, ACI 364 [3] and deterioration of these structures has drawn the attention of the authorities and has affected the image of durability which reinforced concrete traditionally has had. However, despite investigations on the durability of concrete, there is still a need for more exhaustive studies in natural settings or across environments which generate robust information on infrastructure responses to environmental conditions.

Information in the literature indicates that the durability of reinforced concrete structures depends on numerous factors such as: design (water/cement ratio, steel quantity, type of construction) [4], materials (cement, aggregates, water), execution (curing time and conditions), and type of environment to which the structure will be exposed (urban, marine, industrial or some combination of these). Some of the most relevant environmental parameters which may influence the durability of these structures are: relative humidity, temperature, and wind velocity and direction. Such variables will determine the type of damage and the degradation mechanism suffered by concrete structures. Some of the types of damage which concrete may exhibit are: attack by sulphates, freezing and thawing, alkali-aggregate reactions, attack by acid substances, reinforcement steel corrosion, cement lixiviation, intemperism and aging [5]. Among these, steel corrosion is one of the most important and has been extensively studied [6,7,8]. In fact, several studies reported in the literature are based on the development of new ways to quantify the corrosion rate of reinforcement steel and in this way predict its residual life [9,10,11,12,13,14].

Such situation has promoted the development of projects which focus on studying the behavior of concrete structures under different conditions. An example of efforts of this type in Latin America is given by an initiative of the DURACON group (Influence of the environment on concrete durability) through a project with the same name and sponsored by CYTED (Program for development of Science and Technology). A total of 11 countries participate in this project (Argentina, Brazil, Colombia, Chile, Cuba, Spain, Mexico, Peru, Portugal, Uruguay and Venezuela) and one of its main objectives is to study the response of concrete structures to different atmospheric conditions within each country. A total of 40 stations with experimental concrete beams were exposed to different environmental conditions, and data on both concrete durability and environmental parameters are being recorded. One of the 13 Mexican stations is in Tampico, Tamaulipas and by means of the DURACON project it was possible to evaluate the effect of the environment on several concrete characteristics and determine its durability based on the corrosion rate ($i_{corr}$), which has been widely used to determine the deterioration status of concrete structures and predict their residual behavior. Nevertheless, it is clear that, independently of the technique used to record the data, corrosion rate results may be in some cases difficult to interpret under conditions of high environmental variability, as well as during initial stages prior to depassivation. In this sense, the use of statistical methods to infer correlations between electrochemical parameters represents a tool of great importance, which however, has been rarely reported in previous studies [15]. The objectives of the present study were to present and statistically analyze the results obtained from measurements taken during the first year of exposure of concrete probes from the Tampico DURACON Project, as well as to verify the statistical weight of the factors evaluated and identify, based on the life stage of the probes, which factor (s) is (are) promoting the corrosion kinetics of the structures under study.

## 2. EXPERIMENTAL PROCEDURE

### *2.1 Specimen fabrication*

The Tampico station includes six DURACON experimental concrete beams. Each beam was 15 x 15 x 30 cm, was made of reinforced concrete, and had six # 3 steel bars (9.5 mm in diameter) which were previously characterized by Troconis et al. (2006). Three probes were fabricated with a water/cement ratio of 0.45, while the other three were made with a ratio of 0.65.

The steel beams were placed inside the probes using one of three possible concrete cover thicknesses: 15, 20 and 30 mm. Figure 1 shows the geometrical design of the specimens used.

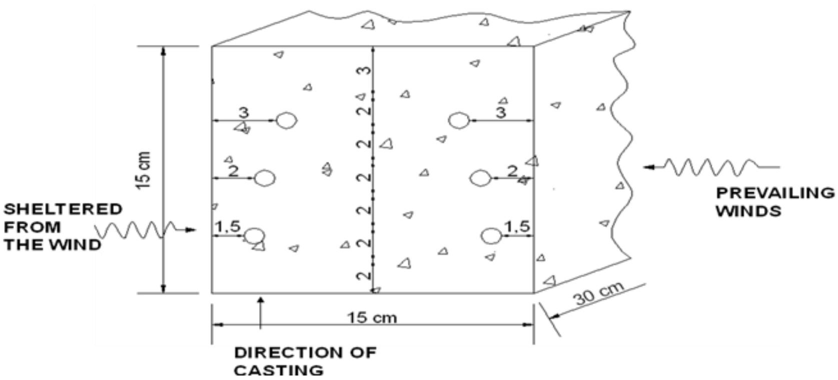


**Figure 1.** Schematic views of transversal and longitudinal sections of reinforced concrete structures used by the DURACON project.

### *2.2 Electrochemical tests*

Concrete beams were subject to measurements of corrosion potential ($E_{corr}$), corrosion rate ($i_{corr}$) and concrete apparent resistivity ($\rho$). All three measures were recorded with a portable corrosimeter, Gecor 6.

The $_{icorr}$ values were obtained by means of the lineal Polarization Resistance Technique (LPR) [15, 5]. Beams were placed in the station with one side facing the prevailing winds (exposed face, EF) and the other sheltered from the wind (protected face, PF). Electrochemical measurements were conducted for both sides of each beam. The side of beam from which the concrete was poured, that is the more porous side, was always sheltered from the wind in order to avoid a preferential entrance of aggressive environmental agents.

*2.3 Data collection*

From January to December of 2006, electrochemical parameters were measured twice a month for all six concrete beams, on both sides and for all three concrete cover thicknesses. This resulted in a total of three replicates, and two repetitions per month for each measured parameter. In order to conduct the non-parametric statistical analysis to determine which factor accelerates the corrosion rate, we evaluated the following effects on the steel electrochemical behavior: a) cover thickness effect (cover factor *cf*; three levels); b) beam side or face effect (beam side factor *sf*; two levels); and c) water/cement ratio effect (ratio factor *rf*; two levels).

*2.4 Statistical analyses*

Prior to conducting statistical tests, a descriptive analysis was performed (for $i_{corr}$, $E_{corr}$ and $\rho$ data) in order to verify assumptions of normality and homogeneity of variances. This exploratory analysis allowed us to confirm that the obtained results were correct based on the statistical tools used [16].

When a data set contains a large degree of dispersion or internal variation and its distribution does not fit that of any known distribution, it is not statistically correct to use the arithmetic mean as an estimator. In this case, non-parametric statistical tests which consider the median as an estimator should be used (the median is not affected by outliers). Although in some cases (such as the present study) it is possible to ignore assumptions of normality and homogeneity of variances, a descriptive analysis of our data set indicated that it contained a large degree of dispersion. Thus, in addition to using a parametric test (factorial analysis), we also conducted a non-parametric test known as the Mood test [17] which allowed us to evaluate if significant differences in the corrosion rate occur due to any of the three factors previously described. This test is based on the comparison of medians between factor levels.

## 3. RESULTS AND DISCUSSION

*3.1 Descriptive statistical analysis*

Figure 2 shows box plots of the corrosion rate for each concrete cover thickness and for both water/cement fabrication ratios. The first box contains measurements recorded for beams which had a water/cement ratio of 0.45 and a thickness cover of 15 mm; the second corresponds to beams with a water/cement ratio of 0.45 and concrete cover of 20 mm, and so on for the remaining boxes. The observed pattern indicates that beams fabricated with a water/cement ratio of 0.45 showed the lowest corrosion rate, as well as the smallest amount of variation. The opposite was observed for beams fabricated with a water/cement ratio of 0.65, which showed greater dispersion values (the highest value within this latter group being for the concrete cover of 20 mm).

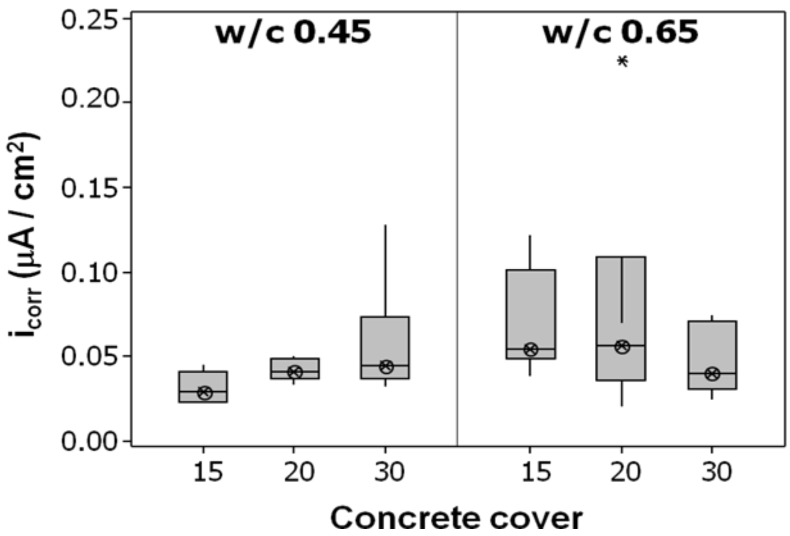


**Figure 2.** Box plots for each water/cement ratio and concrete cover level.

Figure 3 shows box plots of $i_{corr}$ values for all three evaluated factors (water/cement ratio, beam side and concrete thickness). This figure is divided in two sections: section a) corresponds to beams fabricated with a water/cement ratio of 0.45, while section b) to beams fabricated with a water/cement ratio of 0.65. Within each section, each of the concrete thicknesses is indicated, as well as the beam side. The $i_{corr}$ values for the exposed side (ES) of beams with a water/cement ratio of 0.45 showed a negligible level of dispersion; on the other hand, dispersion values were much greater for beams with a water/cement ratio of 0.65, for which the ES showed the greatest values. From this we conclude that beams with a ratio of 0.45 follow a more stable or homogeneous corrosion rate behavior. This type of graph is very useful and important in order to visualize and describe the behavior of the data within each factor, both separately and together.

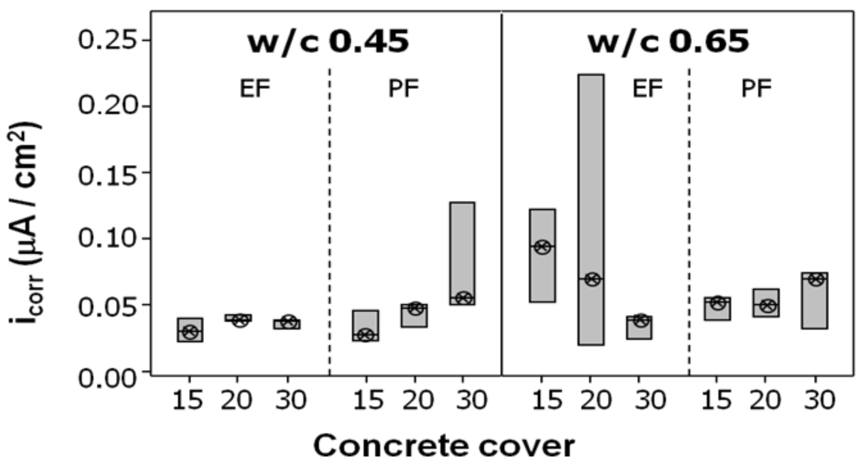


**Figure 3.** Box diagrams divided by water/cement ratio level and within each ratio level the concrete cover and beam side levels are indicated.

In order to conduct an ANOVA it is necessary to satisfy statistical requirements for parametric tests. The first is that the data should fit a normal distribution, which in this case was not achieved based on a normality test conducted which resulted in a P-value of 0.001[1]. The second requirement is homogeneity of variances, and this was satisfied. These findings offered only a partial justification for conducting an ANOVA. Thus, we decided to conduct a non-parametric test which used the median instead of the average (arithmetic mean) to test for significant differences due to the evaluated factors

### *3.2 Non-parametric analysis: Mood test of median differences*

Based on the results obtained from the descriptive analysis we proceeded to conduct the Mood test of median differences. This test allows to compare only one factor at a time, thus making it necessary to conduct the analysis three times (for each factor). We tested three hypotheses: a) that for the *cf* factor, Ho: the corrosion rate medians are not different between concrete cover thickness levels, Ha: at least one pair of medians are different; b) that for the *rf* factor, Ho: there is no difference in the corrosion rate median between beams fabricated with each water/cement ratio, Ha: medians between beams fabricated with each water/cement ratio are different; and finally c) that for the *sf* factor, Ho: there are no differences in corrosion rate between beam sides (0=exposed, 1=protected), Ha: corrosion rate medians are different between beam sides.

**Table 1.** Results from the Mood test of median differences.

| | Mood test: Results | Individual CI 95.0% |
|---|---|---|
| icorr vs. *cf* | Chi- square = 14.29 DF = 2<br>P =0.001<br>Cover N<= N> Median Q3-Q1<br>15 124 146 0.0385 0.0530<br>20 122 148 0.0390 0.0542<br>30 161 109 0.0315 0.0293 | Cover -----+---------+---------+---------+-<br>15 (--------*--------)<br>20 (-------*----------)<br>30 (-------*-)<br>-----+---------+---------+---------+-<br>0.0300 0.0360 0.0420 0.0480 |
| icorr vs. *rf* | Chi- square = 33.19 DF = 1<br>P = 0.000<br>Ratio N<= N> Median Q3-Q1<br>0.45 249 165 0.0270 0.0362<br>0.65 158 238 0.0415 0.0455 | Ratio --------+---------+---------+--------<br>0.45 (--*-------)<br>0.65 (-----*-------)<br>--------+---------+---------+-------<br>0.0300 0.0360 0.0420 |
| icorr vs. *sf* | Side N<= N> Median Q3-Q1<br>0 214 191 0.0330 0.0425<br>1 193 212 0.0370 0.0445<br>P = 0.0802 | Side +---------+---------+---------+--------<br>0 (-----------*-------)<br>1 (---------*---------)<br>+---------+---------+---------+------<br>0.0280 0.0320 0.0360 0.0400 |

The Mood test of median differences provides an output in the form of a table (table 1). Rows correspond to each of the factors tested, and column 2 shows the Chi-square estimators and P-values

"P-value is the probability of having a value of the test statistic as extreme as or more extreme than that observed by chance alone, given that the null hypothesis H0, is true"[1]; if the P-value is greater than 0.05 the null hypothesis is accepted, while if it is smaller than 0.05 the null hypothesis is rejected and the alternative hypothesis is accepted. This is for tests with a 95% confidence level.

which are used to conclude if the effect was statistically significant or not. N<= means the number of observations for each level of a given factor which are smaller or equal to the overall median; N> is the number of observations for each level of a given factor which are greater than the overall median; Median refers to the median value of the observations for each level; Q3-Q1 corresponds to the interquartile range for each factor level (dispersion measure); finally, General median corresponds to the overall median of all observations. Column 3 shows the degree of dispersion in the data; the larger the line overlap, the least significant a factor was.

The results obtained from these tests are shown in Table 1. Based on the P-values shown in the second column of this table it is possible to conclude that factors *cf* (cover thickness) and *rf* (water/cement ratio) were statistically significant with P-values of 0.001 and 0.000, respectively. In other words, this means that the corrosion rate varied significantly between water/cement ratios, as well as between concrete cover thickness levels. The *sf* factor (beam side) did not have a significant effect, which means that the corrosion rate did not vary between exposed and protected sides of each beam.

The last column of Table 1 shows 95% confidence intervals (CI) for the $i_{corr}$ data. The effect of concrete cover thickness on the corrosion rate is first presented, indicating that corrosion rate values were lowest for the 30 mm concrete cover. In the case of the water/cement ratio, the recorded values were much greater for the ratio of 0.65. Finally, an overlap in the confidence intervals for each of the beam sides was observed, indicating non-significant differences between the levels of this factor

In order to obtain more information from the data set, we also conducted a parametric factorial analysis. This analysis however, was only conducted to confirm results from the Mood test. This is because despite the data showing homogeneity of variances, it also showed to be biased which favors the use of a non-parametric test over a parametric one

### *3.3 Parametric test: factorial analysis*

Similar to the Mood test, the ANOVA result for the Factorial Analysis [18,19] also showed significant effects of water/cement ratio and of concrete cover (P values of 0.000 in both cases). This means that the corrosion rate differed significantly between beams fabricated with each water/cement ratio, as well as between concrete cover thickness levels. The beam side effect however, did not have a significant effect on the corrosion rate (P value of 0.657), meaning that the corrosion rate did not differ significantly between beam sides.

The Factorial Analysis provided a graphical representation for which the greater the slope of the line, the larger the effect of a given factor on the behavior of the response variable. Figure 4 shows the effects each studied factor had on the corrosion rate. From this graph it is possible to observe that concrete cover thickness and water/cement ratio had a greater influence on the $i_{corr}$ behavior, while the beam side factor did not to have any effect. Specifically, the lowest $i_{corr}$ values were recorded for the water/cement ratio of 0.45 and the concrete cover of 30 mm. Based on this type of analysis it is possible to determine if any of the evaluated factors had an influence on the obtained results, as well as the magnitude of such effect in order to determine which beam factor or factors had the greatest effect on the structure's durability.

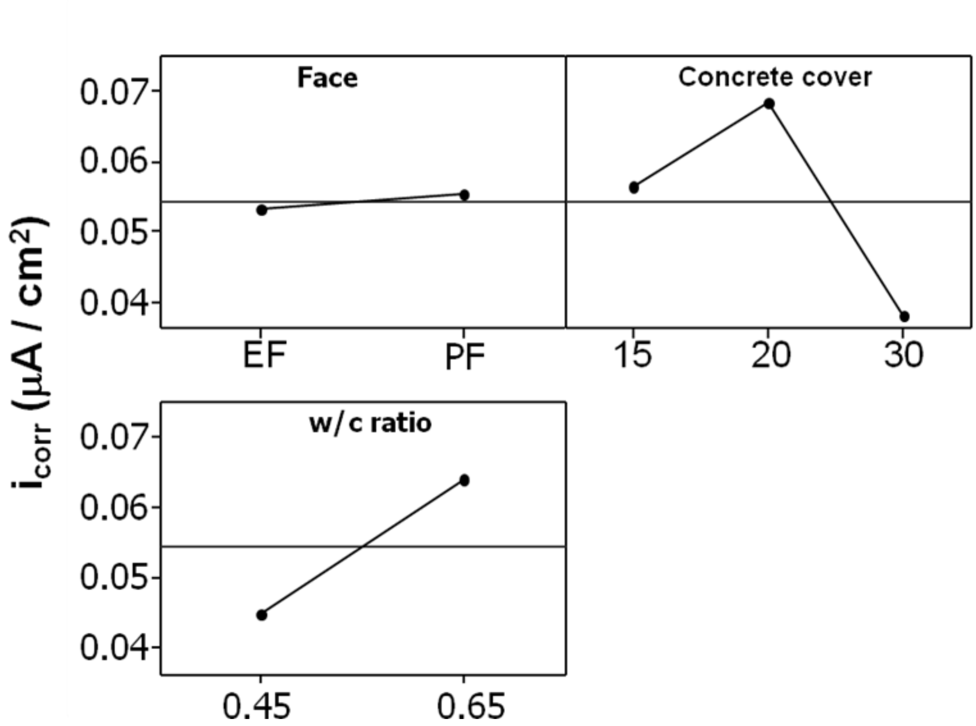


**Figure 4.** Main effects from the factorial design.

Figure 5 shows the effects of each analyzed factor, both independently and together. The first row shows the effect of concrete cover thickness (*cf*) *versus* beam, water/cement ratio (*rf*) and beam side (*sf*) effects, respectively (Figure 5a, 5b and 5c). The second row shows each beam under study *versus* the water/cement ratio and beam side, respectively (Figure 5d and 5e). The third and last row analyzes the effect of water/cement ratio *versus* the beam exposure side (Figure 5f). The greater slope the larger the effect of the analyzed factor on the response variable. For instance, the concrete cover thickness effect together with the water/cement ratio effect (row 1, Figure 5b) indicated that the water/cement ratio effect (in terms of $i_{corr}$) decreased as concrete cover thickness increased. The second row shows that the $i_{corr}$ behavior is much less variable when using a water/cement ratio of 0.45 compared to one of 0.65 (see Figure 5d). The last graph shows that the water/cement ratio effect had a greater influence on the corrosion rate compared to the beam side effect for which no variation between factor levels was observed (Figure 5f).

Based on the field data collected here, non-parametric statistics such as the Mood test of median differences allowed us to determine that both concrete cover thickness and water/cement fabrication ratio had a significant effect on the corrosion rate, even at early stages of the experiment given initial signs of passivation based on electrochemical measures. From a practical standpoint, a non-parametric analysis such as that given by the Mood test may be used to evaluate if other factors influence corrosion rate of concrete structures under a different set of environmental conditions and during early stages of experimentation.

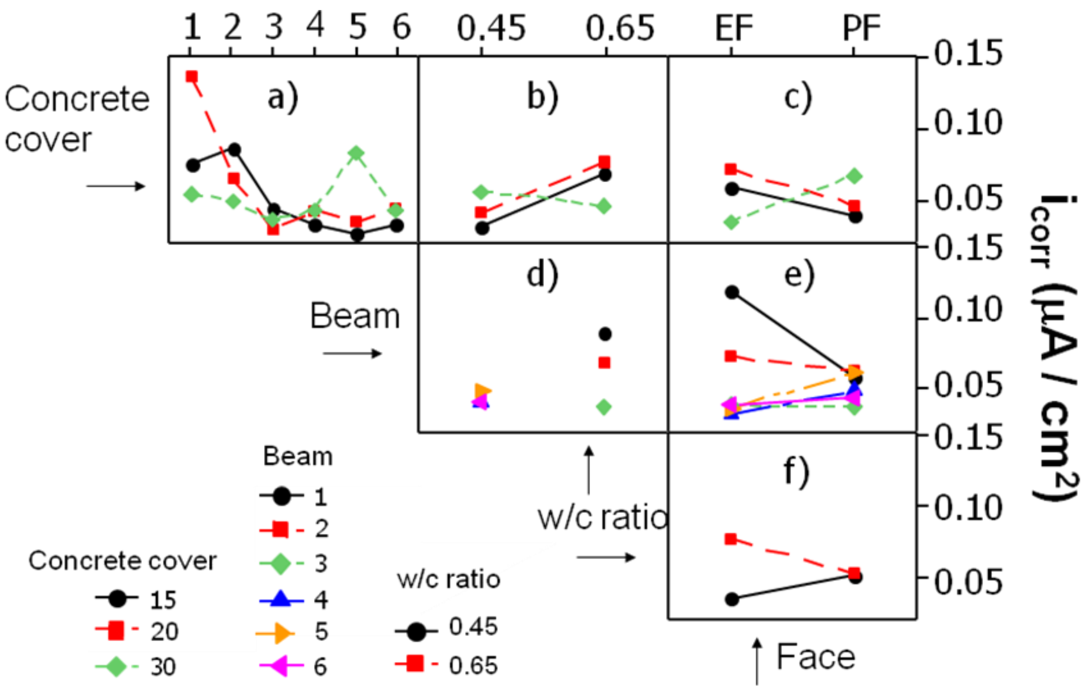


**Figure 5.** Graph for the iteration factors from the factorial analysis.

## 4. CONCLUSIONS

The results obtained from this study show that it is possible to employ statistical techniques to determine which factor or factors have a significant influence on the behavior of the corrosion rate of concrete structures. Given that the data did not follow a normal distribution, the Mood test of median differences allowed us to determine if significant differences existed between levels for the evaluated factors. Two of the tested factors (concrete cover and water/cement ratio) had a significant effect on the corrosion rate during the duration of the experiment. Specifically, the greatest corrosion rate values were generally observed for concrete covers of 15 and 20 cm, as well as for beams prepared with a water/cement ratio of 0.65.

In addition, we observed that beams made with a water/cement ratio of 0.65 presented a greater variability in corrosion rate values compared to those prepared with a ratio of 0.45. Nonetheless, the corrosion rate was not different between beam sides.

Through the use of statistical techniques it was possible to determine that the factors which had the greatest influence on the corrosion rate were the concrete cover and the water/cement preparation ratio (even though the recorded values were within the passivation zone). It is to be expected that for systems with an active form of corrosion it will be possible to obtain a more precise assessment of the factors which influence the corrosion rate.

Since the practical point of view, although electrochemical measurements around depassivation obviously denote no action of the coating or the type of aggressive agent, statistical tools can show this lack of action. Therefore, when evaluating other parameters, statistical tools can help to take preventive/corrective actions in the concrete of nuclear or other critical facilities even if the electrochemical values are as low as those showed here.

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