Corrosion potential: influence of moisture, water-cement ratio, chloride content and concrete cover

Potencial de corrosão: influência da umidade, relação água/cimento, teor de cloretos e cobrimento

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Abstract

The corrosion potential technique is used as an electrochemical method to support the monitoring of reinforcement corrosion in reinforced concrete structures. The corrosion potential ranges and its correlation with corrosion's likelihood (recommended by ASTM C 876:2015) are usually employed as an evaluation criterion of the results. The thermodynamic state of corrosion in the structure or specimen (laboratory) can be established if these criteria are well used. However, the method is influenced by numerous factors related to the concrete, environment and the procedures adopted at the time of the test. In order to provide useful information to technical and scientific community for the correct use of this type of non-destructive evaluation technique, the aim of this article is to evaluate some of the possible factors of influence on the corrosion potential measures, such as concrete moisture content, water-cement ratio, thickness of the concrete cover and degree of chloride contamination. The results indicate that moisture and the degree of chloride contamination tend to make more electronegative corrosion potential. Furthermore, the influence of concrete cover is different for concrete contaminated (1% of chloride by weigh of cement) and not contaminated by chlorides: the influence of the cover thickness in the concrete contaminated with chlorides was reverse because the greater the cover thickness, the least electronegative corrosion potential value; on the other hand, in the concrete without contamination by chlorides, the effect of the cover thickness in corrosion potential readings was irrelevant. All these statements were proven with 95% statistical significance.

Keywords: corrosion potential, concrete moisture content, water-cement ratio, chloride, concrete cover.

Resumo

O método de medida de potencial de corrosão é utilizado como uma ferramenta eletroquímica de auxílio ao monitoramento da corrosão das armaduras de estruturas de concreto armado. Como critério de avaliação dos resultados, é comum que sejam adotados os intervalos de potencial de corrosão e sua correlação com a probabilidade de corrosão, preconizadas pela ASTM C 876:2015. Com este critério é possível estabelecer um panorama da situação termodinâmica de corrosão na estrutura ou no corpo de prova em laboratório. Porém, o método é influenciado por inúmeros fatores relacionados ao concreto, ao ambiente e aos procedimentos adotados no momento da realização das leituras. Visando fornecer informações para orientar o meio técnico e científico ao uso correto deste tipo de método de avaliação não destrutiva, o objetivo deste trabalho é avaliar alguns dos possíveis fatores de influência nas medidas de potencial de corrosão, tais como: teor de umidade do concreto, relação água/cimento, espessura do cobrimento das armaduras e grau de contaminação por cloretos. Os resultados indicaram que a umidade e o grau de contaminação do concreto por íons cloretos tenderam a tornar o potencial de corrosão mais eletronegativo. Além disso, foi verificado que a influência do cobrimento é diferente para o caso de concreto contaminado (1% de cloretos em relação à massa de cimento) e não contaminado com cloretos: a influência da espessura de cobrimento, no caso do concreto contaminado com cloretos, foi inversamente proporcional, ou seja, quanto maior a espessura de cobrimento, menos eletronegativo foi o valor do potencial de corrosão; por outro lado, nos casos de concretos moldados sem a contaminação por cloretos, o efeito da espessura de cobrimento nas leituras de potencial de corrosão foi irrelevante. Todas estas afirmações foram comprovadas com 95% de significância estatística.

Palavras-chave: potencial de corrosão, teor de umidade do concreto, relação água-cimento, cloretos, cobrimento.

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1.   Introduction

Corrosion of concrete reinforcements is one of the possible mechanisms of degradation reducing the resistant capacity of reinforced concrete structures. The speed of deterioration, in these cases, is variable according to several facts, intrinsic to the execution and use of the structures.

The presence of microcraks is the priority access regarding the input of aggressive agents inside the structures. Once having direct access to the reinforcements, the aggressive agents start the corrosion process in the reinforcements acting together with the electrolyte (water) and oxygen – the micro and macro corrosion stack phenomenon.

Factors interfering in the corrosion process are: exposure environment, conditions of the structure, efficient or deficient cover and penetration of aggressive agents inside the concrete and even materials used during concreting.

According to Andrade & Alonso [1] and Assouli et al. [2], the open circuit corrosion potential and electrical resistivity are the most common techniques for evaluating the corrosion of reinforcements, even if they are merely qualitative techniques evaluating the thermodynamics of the process, not providing data about the kinetics of the phenomenon. Despite this affirmation being more than 10 years old, the method of corrosion potential continues to be one of the more common electrochemical tools for helping the inspection, monitoring and diagnostic of the corrosion of the reinforcements of concrete structures [3], being cited as a method of monitoring in inspection works in the field as recorded in the following studies: Andrade & Alonso [1]; Liam et al. [4]; Helene [5]; Broomfield et al.

[6]; Elsener et al. [7]; Feliu et al. [8]; Helene et al. [9]; Poupard et al. [10]; Castro-Borges & Ordaz [11]; Medeiros et al. [12]; Castro-Borges et al. [13]; Medeiros et al. [14,15].

This method has also been used to evaluate the efficiency of repair systems, measuring the repassivation capacity of reinforcements in concrete submitted to extraction of chlorides, besides testing the efficiency of realkalisation and corrosion inhibitors [16]. Besides, McCarter and Vennesland [17] applied the open circuit potential as the principle for elaborating a corrosion sensor for reinforced concrete structures.

In the context about the importance and representativeness of this method in works of inspection and diagnosis of reinforced concrete structures, the objective of this work is to evaluate the influence of some factors in the readings of corrosion potential in order to provide information to guide the technical and scientific sectors using this kind of non destructive evaluation technique. Factors evaluated in this work are: moisture content, water-cement ratio, concrete cover thickness and degree of chloride contamination.

2.   Corrosion potential

The measurement of corrosion potential is used to classify the probability of corrosion of carbon steel reinforcements immersed in concrete, according to ASTM C 876:2015 [18], being possible to use it for monitoring reinforced concrete structures along time [5]. This tool is a fast and low cost way of identifying depassivation layer of steel needing analysis or repairs [14]. Reinforcing the applicability of the assay, study from Pradhan and Bhattacharjee [19] corroborates with the information that corrosion potential is an effective measure for finding the beginning of the corrosion of
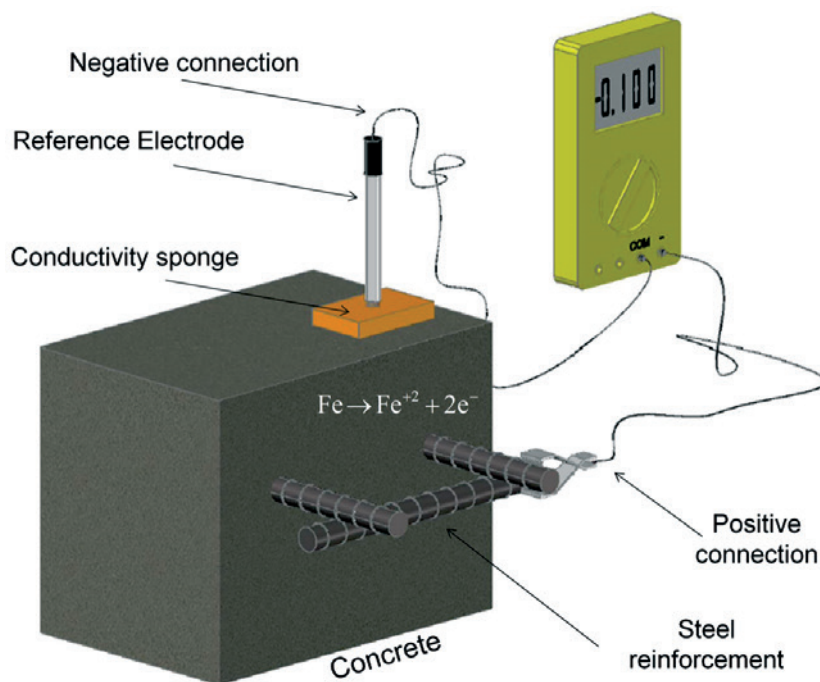
Figure 1
Configuration of circuit for determination of corrosion potential (ASTM C 876:2009 (18) adapted by ROCHA (21))

reinforced concrete structures exposed to environments contaminated by chlorides.

The corrosion potential of the reinforcements is a mixed potential, resulting from the combination of the kinetics of two processes: (1) metal oxidation, and (2) reduction of dissolved oxygen [20]. The method consists in measuring the difference of electric potential between the steel and a reference electrode, with the last one being able to keep its electric potential stable. Figure 1 shows the system configuration needed, where the reference electrode supported is illustrated immediately after the surface of the concrete covering the reinforcement, the high impedance voltmeter and the electric connection with the steel bar (indispensable for executing the readings).

According to Song and Saraswarhy [22], the aqueous solution contained in the network of pores in the concrete acts as an electrolyte and, thus, the steel develops an electric potential that may vary from one place to another of the structural pieces as a function of discontinuities that may be generated in the reinforced concreted structure such as: carbonation, chloride contamination, variations in porosity and moisture, among others. Assouli *et al*. [2] also corroborate regarding the effect of these sources of discontinuities in the readings of the corrosion potential of concrete reinforcements. The equipment used for measuring the corrosion potential consists in a voltmeter (able to record measurements of potential difference), a reference electrode and a high conductivity sponge. As reference electrode it is usual to use a copper/copper sulfate electrode. This electrode is composed by a plastic or glass tube, inside which there is a copper rod immersed in a saturated aqueous solution of copper sulfate. In order to ensure the saturation of the aqueous solution it is worth to always use an amount of copper sulfate enough to cause the accumulation of this compound at the bottom of the solution. The contact end of the electrode is made by a porous point in order to proportionate the electrical continuity of the reference electrode with the work electrode (iron/concrete system). Darby *et al.* [23] showed, in their technical guide for testing and monitoring the durability of concrete structures that the voltmeter may be replaced by a digital voltmeter, provided that it has a minimal impedance of 20 MΩ.

The evaluation criterion of results defined by ASTM C 876:2015 [18] is in Table 1. Those values, as the mentioned standard precognizes, should not be considered as absolute, being accepted only as reference ranges. If well used, and results are combined with determinations of chlorides' amount, electric resistivity of concrete and depth of carbonation, for instance, it is possible to establish a perspective of the situation of corrosion in the reinforced concrete structure or in the test specimen in laboratory by mapping the inspected piece, indicating areas with different probabilities of corrosion. According to Romano *et al*. [20], most of the studies dealing with the systematic monitoring of reinforced concrete structures do not use only one technique of inspection, but the combination of several evaluation methods, contributing to obtain more reliable information regarding the situation of the corrosion of structures. Gonzalez *et al*. [24] argument that the corrosion potential must be interpreted together with the electrical resistivity of the concrete and with the corrosion rate of the steel. Besides, the reference electrode may be moved over the surface of the concrete in order to develop a map of potential showing the possible places of active corrosion in the structure [25,26]. The work of Pour-Ghaz *et al*. [27], with the title "Quantitative Interpretation of Half-Cell Potential Measurements in Concrete Structures" follows this same line of reasoning and presents a proposal for the quantitative evaluation of corrosion potential together with electrical resistivity, cover thickness and temperature.

3. Experimental program

For the experiment of this research, the following independent variables were determined:

■ **Thickness of reinforcement cover (2 levels: 1 cm and 3 cm);**
Reason: the criterion was to simulate covers likely to exist in conditions of real buildings. The concrete cover of 1 cm was chosen for simulating buildings that do not comply with the minimum coverage established in engineering projects, but that are still part of the reality of many operating buildings. On the other hand, the concrete cover of 3 cm was chosen for simulating pillars and beams in marine atmosphere in an internal and protected environment (class of aggressiveness II of NBR 6118:2014 [28]).

■ **Degree of contamination of concrete (2 levels: without chlorides added to concrete and 1% of Cl⁻ regarding the cement mass in the moment of the concrete mix);**
Reason: Thomas [29] developed an experiment that evidenced that 0.70% of total chlorides, regarding the cement paste, is a critical limit for depassivation of the carbon steel inside the reinforced concrete. Nygaard and Geiker [30] also evidenced the critical amount for depassivation of reinforcements under contaminating conditions by chlorides as being between 0.52 and 0.75% of the total chlorides regarding the cement paste. Both studies were executed with cements similar to the one used in this experiment. Based on this information, and intentionally aiming to produce a concrete with a degree of contamination by chlorides causing the depassivation of reinforcements, the

Table 1

Ranges of corrosion potential and their correlation with corrosion probability according to ASTM C 876: 2009 (18)

Copper /Copper sulfate electrode	Corrosion probability
More negative than – 350 mV	Over 90%
More positive than – 200 mV	Under 10%
From – 200 until – 350 mV	Uncertain

Table 2
Summary of the proportions of materials in concretes

m	Cement	Sand	Gravel	w/c	Slump (mm)	Cement content (kg/m³)	Compressive strength (MPa)	Specific mass of concrete (kg/m³)
3	1	1.08	1.92	0.43	105	540	50	2390
4	1	1.60	2.40	0.50	90	421	41	2315
5	1	2.12	2.88	0.59	95	346	30	2280

option of adding 1% of chlorides regarding the cement mass in the mixture of concrete in fresh state was taken.

■ **Moisture content in concrete (variable as a function of the moisture state of the concrete);**

Reason: This is the first parameter that varied as a function of environmental conditions to which the test specimens were submitted. The focus of this stage was to make the internal moisture of the concrete to vary under controlled conditions, specifically to investigate the result of this interfering factor on the readings of corrosion potential.

■ **Water/cement ratio (3 levels: 0.43; 0.50 and 0.59), for a same consistency (100±10 mm).**

Reason: in order to keep the coherence of simulating edification in the aggressiveness class II of NBR 6118:2014 [28], it was decided to use, in this experiment, concretes with water/cement ratio under 0.60. The water/cement ratios indicated in this item are reflexes of applying the method of dosing from IBRACON [31], taking the care of not exceeding the already mentioned water/cement limit ratio.

3.1 Test specimens

Twelve prismatic test specimens of reinforced concrete were produced for the experiment, with dimensions of 15 x 15 x 45 cm, simulating a stretch of a reinforced beam. The traces (relation cement:aggregates) in mass 1:3. 1:4 and 1:5 were used. It is important to point out that this range of variation comprises conventional concretes it terms of compressive strength, in other words,

having a large applicability of those traces in general buildings. In each molding date two prismatic test specimens were molded. Table 2 presents the traces of concrete defined for casting the test specimens, which were executed using the dosing method from IBRACON [31].

In each test specimen, four steel rods were distributed, positioned with concrete cover thicknesses equal to 1 cm and 3 cm in Faces 1 and 2 respectively, as shown on the schematic representation in Figure 2. It is important to highlight that the four rods had 10 cm outside the concrete element in each extremity of the test specimens, serving as a contact area for the equipment of corrosion potential.

Two test specimens for concrete with chlorides and two without chlorides were produced for each one of the three concrete mixtures, in a total of twelve prisms of concrete.

The prismatic test specimens remained in wet chamber (95% of R.H and 23±2°C of temperature) until day 70. This long cure period was chosen for simulating real structures who suffer the need of field tests, in other words, concrete with advanced degree of hydration along its service life.

At the end of the mentioned cure period, all test specimens were transferred to a laboratory with conditions of controlled environment in 23±2 °C and relative humidity between 65 and 75%. The reason for this change of environment is supported by the fact that, in this moment, the test specimens enter the drying regime and this paper has, as one of its objectives, to study the influence of moisture in the readings of corrosion potential. Thus, this procedure allowed executing readings under different conditions of internal moisture of the concrete.
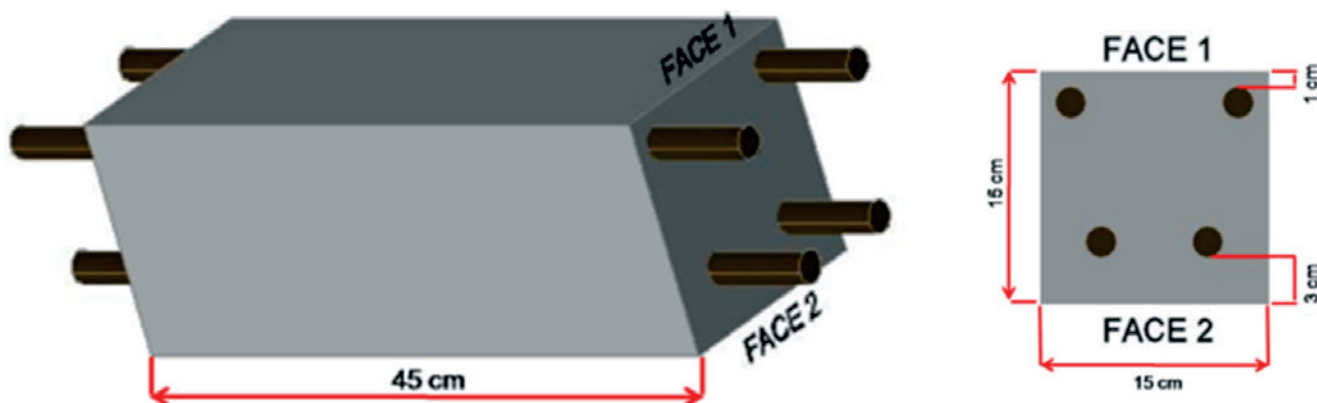
Figure 2
Schematic representation of prismatic test specimens

3.2 Materials

Materials used for producing the test specimens were:
- Cement CP II-F-32, with 6% to 10% of calcareous filler (characterized in Table 3);
- Coarse aggregate, with modulus of fineness equal to 6.94 and dimensions between 9.5 and 25.0 mm;
- Natural sand with fine aggregate, with modulus of fineness equal to 2.23;
- Carbon steel rods, type CA50, with 10 mm diameter and 65 cm length, which underwent a cleaning process similar to the one used by Medeiros [32];
- Water from "Companhia Paranaense Sanepar";
- NaCl incorporated into the water of the test specimens, with controlled contamination.

All materials used for dosing the concretes of this experiment were obtained by donation from a concrete production plant located in Curitiba, Brazil. This way, they are materials effectively used in the composition used in real buildings and, because of that, they were chosen for this experiment. Besides, steel CA50, in the shape of bars with 10mm of diameter, was also chosen because it is an option frequently used in the existing structures.

3.3 Test procedures

Readings of corrosion potential were executed using a high input (>20 MΩ) impedance voltmeter connected to a reference electrode of copper/copper sulfate and to the reinforcement of the test specimens. In order to improve the electric conductivity between the reference electrode and concrete, a sponge humidified with water was positioned in the contact surface between both at the moment of readings.

The chronogram of readings was established according to the curing conditions of the concrete, as well as according to their evolution along time. Readings were executed in three stages:

- **Stage 1: at 70 days, conditioned in wet chamber since casting;**
  Reason: simulating a structure operating for many years, with hydration of cement in advanced stage. Those structures are

normally objects for measuring the corrosion potential, because they have been under degradation process along the years.
- **Stage 2: at 98 days, kept in laboratory environment (temperature of 23±2 °C and moisture between 65 e 75%) since day 71;**
  Reason: To study the influence of the saturation degree of the concrete over the corrosion potential readings, since all test specimens left the saturation condition (Stage 1) and passed by an environment leading to concrete drying.
- **Stage 3: after one year of casting, test specimens were submitted to immersion in water during two days and a new series of readings executed in the test specimens.**
  Reason: Investigating the corrosion potential, after one year, of the pieces of reinforced concrete in operation.

Reading consists in the potential difference (ddp) between the parts involved in the test (unstable electrolyte – steel/concrete system – and another one stable – reference electrode).

The planning of the tests comprised the realization of readings in the two faces of the test specimens, with different cover thicknesses, in a total of 12 points (6 points in each face), previously determined and symmetrically distant between them. Thus, each piece of the same trace and contamination level propitiated 6 readings regarding the 2 bars of the same cover. The result was a total of 12 readings, considering the 2 pieces for each trace, each cover thickness and each level of chloride contamination. Figure 3 shows a schema of the reading points in a face of the test specimen.

In order to make feasible the determination of the moisture content of the test specimens, at 70 and 98 days, it was necessary to obtain the mass of the test specimens at the moment of the corrosion potential readings. The mass of the test specimens in dry state was obtained by drying them in oven at 60 °C until mass constancy, right at the end of Stage 2 and in the same test specimens used in all monitoring. Moisture content was obtained as a percentage of the mass of the test specimens used during the whole monitoring. Moisture content was obtained as a percentage of the mass of the test specimens in dry state.

All results of this experiment were analyzed by the statistical method of variance analysis (ANOVA).

Table 3
Physical, mechanical and chemical characteristics of cement CP II F – 32

Chemical analysis								
CaO (%)	SiO$_2$ (%)	Al$_2$O$_3$ (%)	Fe$_2$O$_3$ (%)	MgO (%)	SO$_3$ (%)	Free CaO (%)	Fire loss (%)	Insoluble residue (%)
59.64	18.35	4.07	2.54	5.19	3.07	1.20	5.35	1.47

Physical and mechanical characteristics									
Expandability in hot (mm)	Start setting time (h)	Final setting time (h)	Normal consistency (%)	Blaine (cm^2/g)	# 200 (%)	# 325 (%)	3 days* (MPa)	7 days* (MPa)	28 days* (MPa)
0.83	03:31	04:10	25.5	3.338	3.87	17.76	25.1	32.0	40.4
* Compressive strength									
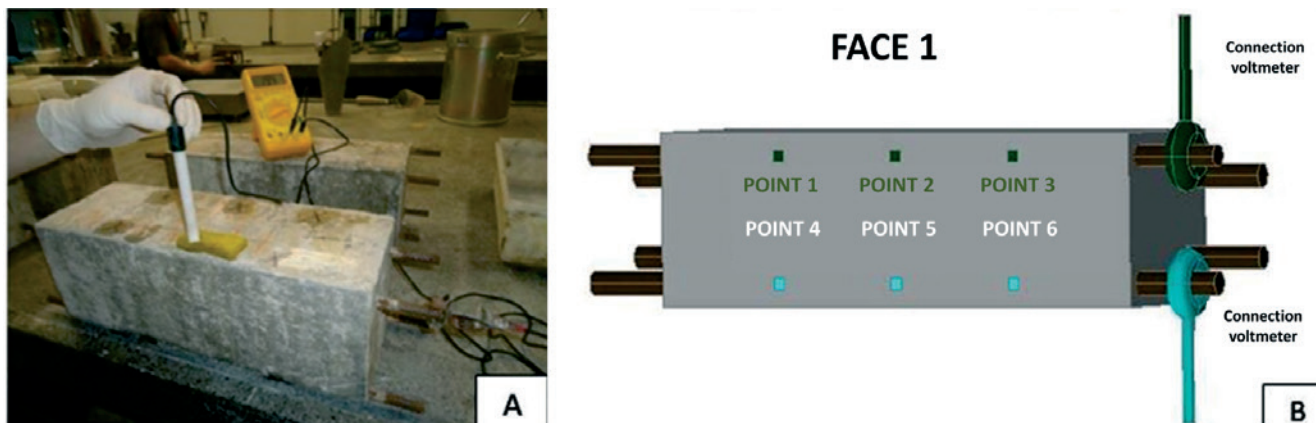
Figure 3
(A) Execution of test for determinating the corrosion potential with high impedance voltmeter;
(B) Positioning of reading points with voltmeter

4. Results and discussions

4.1 Influence of moisture content

The effect of the moisture content inside the test specimens was analyzed in two moments: at 70 days (Stage 1) and at 98 days (Stage 2). Those dates were chosen because they are extremes of two adverse monitoring conditions. The first with moisture content over 95% and the second in laboratory environment with average temperature of 23°C and moisture content between 65 and 75%. Results are shown in Figure 4.

It is worth to highlight that data of corrosion potential for Stage 3 (age between 425 and 450 days) were not used in this evaluation, because the ages of the samples are very different between themselves and could compromise the comparison of data.

It is possible to observe that the corrosion potential is more negative for greater moisture contents, as also evidenced by Elsener et al. [7] and Leelalerkiet et al. [33]; in other words, corrosion potentials at 70 days measured in the test specimens that were in humid environment (saturated) are more negative than corrosion potentials at 98 days (drying in laboratory environment between 71 and 98 days), when the test specimens had a smaller moisture content.
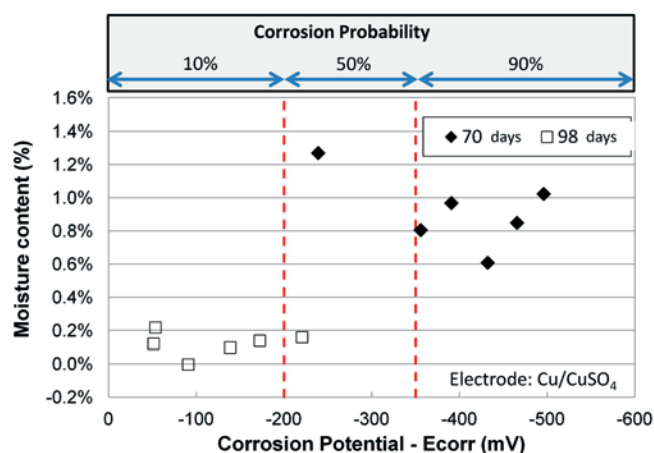
The interaction between moisture content and corrosion potential is significant and this fact was evidenced by means of variance analysis ANOVA (Table 4), where the value of F calculated is higher than the F critical tabulated for 95% of significance. This behavior is coherent with recommendation from Helene [5] and Poursaee and Hansson [34] about previously saturating the pieces of reinforced concrete (at least one hour before) for starting the corrosion potential readings. According to Medeiros et al. [15], this practice is adopted in works of inspecting reinforced concrete structures in order to execute the corrosion potential readings under the worse possible condition. The trend of the corrosion potential value becoming more negative as the concrete becomes more humid is substantiated in the increasing of the electric potential of the concrete, facilitating the electrical contact between the reference electrode and the steel bar,

which is the focus of the corrosion state measurement. Gonzalez et al. [24] also discuss the importance of moisture on the readings of corrosion potential. According to these authors, the same steel immersed in carbonated concrete, or contaminated by chloride, may indicate probability of active or passive corrosion according to classification of ASTM standard C-876/2015 [18], depending on the moisture content of the concrete at the moment of the inspection work.

It is worth to highlight that from this point, the interpretations will be placed substantiated in the technique of variance analysis (ANOVA), however tables similar to Table 4 will not be presented in order to avoid making this paper too extensive.

4.2 Influence of water/cement ratio

Following are presented analyzes for the three stages of the experiment, verifying the influence of the water/cement ratio on the corrosion potential.

Figure 4
Correlation between corrosion potential and moisture content

Table 4
Statistical treatment – ANOVA for interaction between moisture content and corrosion potential (95% of significance)

ANOVA						
Source of variation	SQ	GL	MQ	$F_{calculated}$	$F_{critical}$	Factor
Humidity levels	433107.512	1	433107.512	31.370	4.301	Significant
Inside groups	303740.667	22	13806.394	–	–	–
Total	736848.179	23	–	–	–	–

4.2.1 Stage 1

In Stage 1, the test specimens remained under curing conditions in wet chamber. Figure 5 does not indicate a clear trend about the influence of the water/cement ratio on the corrosion potential readings. However, using ANOVA with 95% of significance, the effect of the water/cement ratio is considered as significant.

It is important to note that for all cases, including traces without chloride, the values of corrosion potential are more negative during this stage, indicating that there is some activity of the corrosion process over the surface of the bars. This is due to the formation of the passivating film of the reinforcements inside the highly alkaline concrete, as also observed in other studies. Araújo [35] found that the formation of the passivating film for water/cement ratios equal to 0.40 and 0.70 happened after 130 days identified by corrosion potentials greater than -200 mV and values of corrosion speed smaller that 0.1 μA/cm². It is known that this film is formed by iron oxides and, as it is being formed, the occurrence of values of corrosion potential more negative than -350 mV is normal, indicating active corrosion process.

4.2.2 Stage 2

After removing the test specimens from the wet chamber cure condition, they were transferred to laboratory environment, with average temperature of 23°C and moisture between 65 and 75%. The test specimens stayed under this condition during 28 days, period called Stage 2. Comparing Figure 6 with Figure 5 (Stage 1), it is possible to see that the potential reached less negative values, especially in the test specimens without contamination by chlorides. This may be explained by the reduction of moisture inside the concrete in face of the new monitoring condition, delaying the corrosion process inside the structures. It was also observed that, in almost all cases, the averages of corrosion potential remained located in the probability zone of corrosion of 10%.

Regarding the influence of the water/cement reaction, in this stage there is also a lack of a clear trend about the corrosion potential readings, as presented in Figure 6. However, with the statistical method of variance analysis, considering 95% of significance, it was once again found that there is significant influence of the water/cement ratio.
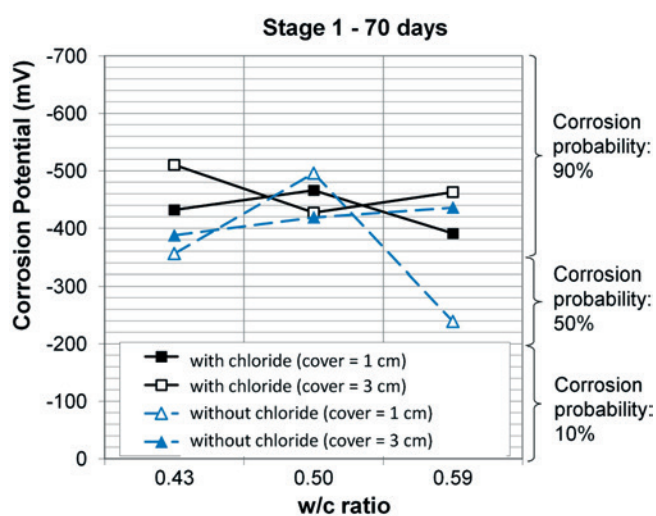
Figure 5
Influence of water/cement ratio on corrosion potential with different traces – Stage 1
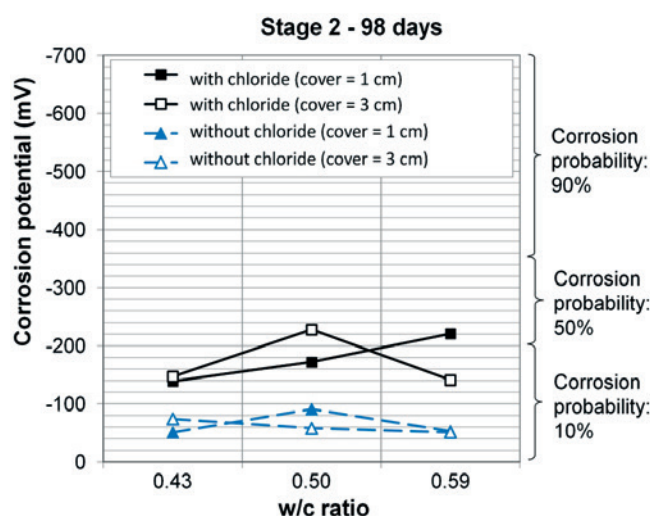
Figure 6
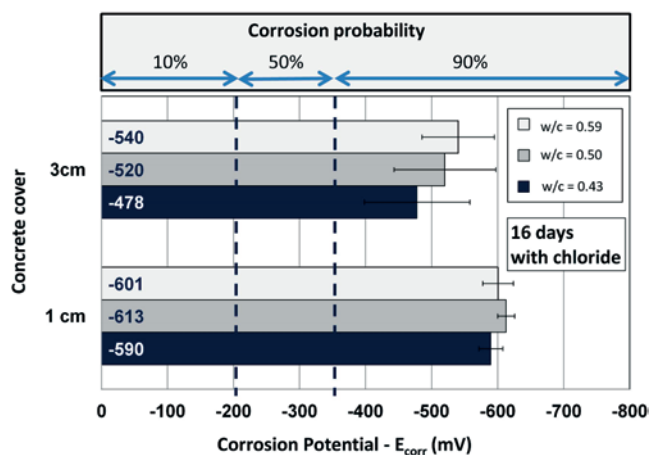Influence of water/cement ratio on corrosion potential with different traces – Stage 2
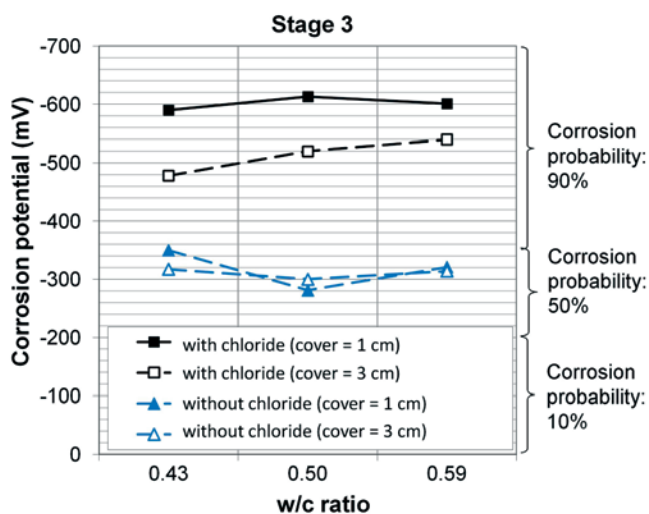
Figure 7
Influence of water/cement ratio on corrosion potential with different traces – Stage 3

4.2.3 Stage 3

The Stage 3 of readings comprised three cycles of immersion and drying during 21 consecutive days. Graphs were obtained according to data of 16 days of cycling, considering the date representing the period in which the test specimens were removed from the condition of immersion for the last week of readings. Figure 7 shows the result of corrosion potential readings at the 16th day of cycling, in other words, right after the exit of the last immersion period of the cycle.

Regarding the ranges of corrosion probability, it is seen that the levels of corrosion potential for traces with or without chlorides are well defined, with greater probability of corrosion (90%) in contaminated concretes and zone of uncertainty for concretes uncontaminated by chlorides.

Regarding the water/cement ratio, a clearer influence is verified in the corrosion potential reading of the trace with chlorides, which may be proved with the statistical method of variance analysis using 95% of significance. For the trace without chloride, variance analysis indicated that the water/cement ratio had no direct influence on the results. Thus, it becomes evident that the influence of the water/cement ratio becomes important by showing a clear tendency of influence when the reinforced concrete is contaminated by chlorides and with enough internal moisture for favoring the corrosion process. It is verified that the greater the water/cement ratio of the concrete is, the more electronegative are the values of corrosion potential. This result is explained by the fact that the network of pores formed in concrete with greater water/cement ratio has a tendency of propitiating a greater input of water, reducing the electrical resistivity of the system and tending to make the values of corrosion potential more electronegative, in the case of concretes with reinforcement debased by chlorides.

4.3 Influence of concrete cover thickness

Figure 8 shows the results of corrosion potential readings at day 16 of the cycling period (Stage 3) for the case of concrete contaminated by chlorides. It is observed that the values of standard deviation for cover equal to 3 cm were greater when compared to the ones of cover equal to 1 cm. This may be explained, because the greater the cover thickness is, the worse the conditions of electric contact between the work electrode (steel bar) and the reference electrode are. Using the analysis of variance for the case of contamination by chlorides it is possible to say that the thickness of the cover directly influences the corrosion potential readings, according to a 95% confidence interval.

Figure 9 shows data regarding concretes not contaminated with chlorides. In this case the effect of the cover thickness is irrelevant, as confirmed by variance analysis applied with a 95% significance level. Coca *et al.* [36] performed a similar experiment in which the influence of the variation of the cover thickness of the reinforcement (1.5; 2.0 and 3.0 cm were tested) in the corrosion potential

Figure 8
Influence of cover on corrosion potential with w/c= 0.43; 0.50 and 0.59 – with chloride
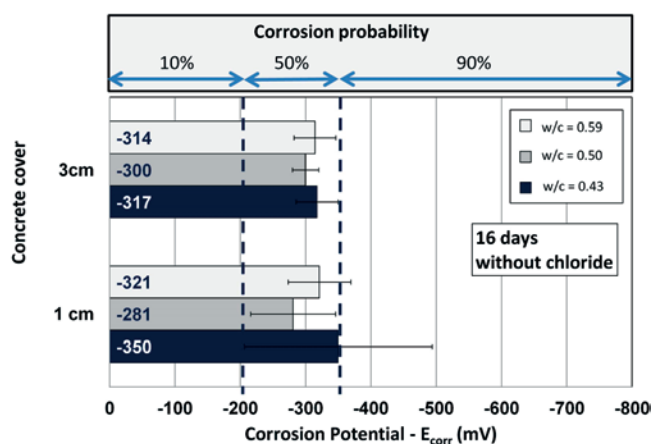
Figure 9
Influence of cover on corrosion potential with w/c= 0.43; 0.50 and 0.59 – without chloride

readings for concretes with water/cement ratios of 0.45 and 0.60 was investigated. In this study concretes were not contaminated by chlorides, neither carbonated, and it was also found that cover thickness has no significant influence on the corrosion potential readings.

Comparing Figures 8 and 9 it is seen that the influence of the concrete cover on corrosion potential readings is different for concrete contaminated by chlorides and for uncontaminated concrete. Thus, cover thickness is an important influencing factor in the first case and in the second case it has no importance to results.

The ranges of corrosion probability are also requisites to be taken into consideration. It is seen that the corrosion potential levels for the two amounts of contamination are well defined, with greater probability of corrosion (90%) in concretes contaminated with 1% of chlorides by mass of cement (Figure 8), and classified as zone of uncertainty in the case of concretes uncontaminated by chlorides (Figure 9).

4.4 Influence of the degree of contamination by chlorides

Despite the comparison between Figure 8 and 9 already allowing understanding the effect of the contamination of concrete by chlorides in the corrosion potential, Figure 10 and 11 also evidence this fact, split by values of the cover thickness of reinforcements, with 1 cm and 3 cm, respectively.

A difference between results is clearly noted: a trend for more negative values of corrosion potential in cases where the concrete is contaminated with 1% of chlorides. This may be asserted with 95% of significance both for the cover of 1 cm as well as for the one of 3 cm. This behavior is explained by the trend of increasing the electrical conductivity coming from the chloride ions in the concrete, as well as by the corrosion activity provided by the presence of those ions, breaking the passivating film and installing the process of reinforcement corrosion.

González *et al.* [24] also had data indicating that contamination by chlorides has a tendency of making the corrosion potential readings more electronegative, corroborating results obtained in this research.

5.   Conclusions

This study produced information contributing to the inspection works of reinforced concrete structures using the technique of corrosion potential.

Influence of the moisture content of the concrete: with data obtained in this experiment it is possible to assert, with 95% of significance, that there is influence of the moisture content on the corrosion potential and that higher moisture contents have a tendency of resulting in more electronegative values of corrosion potential due to the increase of the electrical conductivity of the system.

Influence of water/cement ratio: it was possible to verify the influence of the water/cement ratio, with the only exception of the trace of concrete without chlorides in Stage 3, when test specimens were exposed to the cycling process. It is worth to highlight, however, that it was not possible to define a clear trend of the water/cement ratio on data of corrosion potential.

Influence of cover thickness: it was verified that the influence of the concrete cover is different for the case of contaminated (1% of chlorides by mass of cement) and uncontaminated concrete. With data obtained and by the variance analysis applied, in the case of concrete contaminated by chlorides, it is possible to assert that the concrete cover has influence on the corrosion potential readings, according to confidence interval of 95%. The influence of the cover thickness in the case of concrete contaminated by chlorides is inverse, in other words, the thicker the cover, the small the value of corrosion potential. In the case of concretes without chlorides, the effect of the cover is irrelevant with 95% of significance.

Influence of degree of contamination by chlorides: with 95% of significance, it is possible to assert that the chlorides have
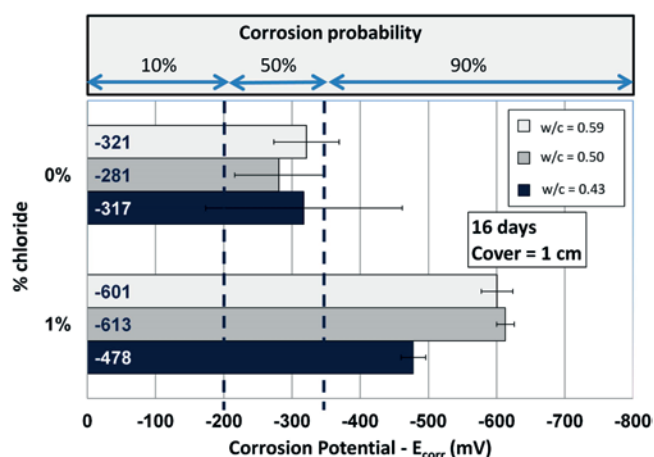
Figure 10
Influence of contamination by chlorides on corrosion potential with w / c = 0.43; 0.50 and 0.59 – concrete cover = 1 cm
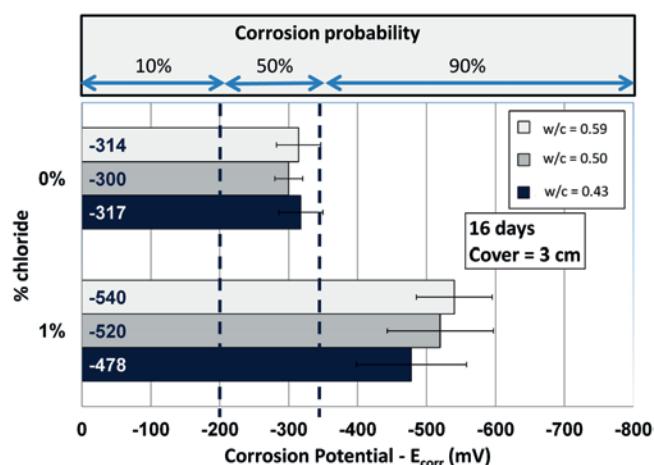
Figure 11
Influence of contamination by chlorides on corrosion potential with w / c = 0.43; 0.50 and 0.59 – concrete cover = 3 cm

influence in the values of corrosion potential. The framing of the ranges of corrosion probability of the two amounts of contamination in this study (0% and 1% of chlorides by mass of cement) is well defined, with uncontaminated concretes classified in the zone of uncertainty and contaminated concretes situated in the zone of 90% of corrosion probability. Thus, it is possible to say that the presence of chlorides reduces the values of corrosion potential.

Regarding the practical aspects of applying the method of corrosion potential for evaluating buildings of reinforced concrete, a great sensibility of readings can be noted regarding ages analyzed in the first stage of the experiment (wet curing period of 70 days). This happened due to the formation of a layer of iron oxide composing the passivating film. Because of that, it is possible to misrepresent the corrosion potentials of the stage of passivating film formation, in a structure with few months of building, with possible zones of active corrosion.

It is important to record that those findings are limited to the executed experiment and to materials used in this research. The generalization of the conclusions is only possible with more studies involving other types of cement, the presence of additives and mineral addictions, as well as other variations in the concrete dosing. However, this work contributes by showing the importance of controlling the access of moisture to the reinforced concrete, of the cover thickness of reinforcements and of the influence of the degree of contamination in the result of the corrosion potential of reinforcements in concrete structures.

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7. References

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