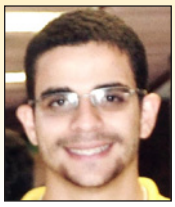
Volume 9, Number 4 (August 2016) p. 595 - 616 • ISSN 1983-4195
http://dx.doi.org/10.1590/S1983-41952016000400008

REVISTA IBRACON DE ESTRUTURAS E MATERIAIS
IBRACON STRUCTURES AND MATERIALS JOURNAL

Effects of the zinc and zinc-nickel alloys electroplating on the corrodibility of reinforced concrete rebars

Efeito da eletrodeposição de zinco e da liga zinco-níquel na corrosibilidade das armaduras de concreto armado





F. A. CEDRIM [a]
felipecedrim@hotmail.com

V. L. S. ALMEIDA [a]
vlsalmeida@hotmail.com

C. A. C. SOUZA [a]
caldassouza@hotmail.com

M. D. JESUS [a]
cheledavid13@yahoo.com.br

D. V. RIBEIRO [a]
verasribeiro@hotmail.com

Abstract

This paper shows the analysis performed on the corrosion parameters of three groups of reinforcing steel bars, two of these coated by electroplating process with Zinc (Zn) and Zinc-Nickel (Zn-Ni), and the other without any coating. It was used reinforced concrete specimens, which ones were grouped and then subjected to two different corrosion accelerating methods: aging wetting/drying cycles and salt spray exposure. Corrosion potential was measured to qualitative monitoring of the process and, after the end of the tests, corrosion rate was estimated by measuring the mass loss, to quantitative analyses. As it was expected, coated bars presented a better performance than the average bars regarding the corrosion resistance in chloride ions containing environments. It was also observed that the drying/ NaCl solution wetting cycles seems to be more severe than salt spray fog apparatus with respect to the acceleration of corrosion process.

Keywords: electroplating, zinc, reinforced concrete, corrosion.

Resumo

O presente trabalho avaliou os parâmetros de corrosão das barras de aço revestidas com Zinco (Zn) e com a liga Zinco-Níquel (Zn-Ni), por eletrodeposição, comparando-as com as tradicionalmente utilizadas, sem revestimento. Para isso, utilizaram-se amostras de concreto armado que foram submetidas a ensaios acelerados de corrosão por ação de cloretos (câmara de névoa salina – "salt spray" e ciclos de imersão e secagem). O potencial de corrosão das armaduras foi medido para monitoramento qualitativo do processo e, após o fim dos ensaios, estimaram-se as taxas de corrosão das barras, através da perda de massa, para análise quantitativa. As barras revestidas com Zn e Zn-Ni se mostraram mais resistentes à corrosão, quando comparadas com as barras convencionais, em ambientes com forte ação de cloretos e o envelhecimento por ciclos se mostrou muito mais eficiente na aceleração do processo de corrosão.

Palavras-chave: eletrodeposição, zinco, concreto armado, corrosão.

[a] *Universidade Federal da Bahia, Departamento de Ciência e Tecnologia dos Materiais, Escola Politécnica, Salvador, BA, Brasil.*

Received: 23 Set 2015 • Accepted: 10 Mar 2016 • Available Online: 12 Jul 2016

1. Introduction

Corrosive processes in reinforced concrete structures put at risk the integrity of their users and have become usual in Brazil, mainly in coastal constructions since most of Brazil's population lives along the coast [1]. It is estimated that around 5% of a nation's GDP (Gross Domestic Product) are spent solving corrosion related problems. In Brazil specifically, this costs exceeds 10 billion of reais per year [2].

Frequently, the durability of the reinforced concrete structures is overlooked, but this matter is extremely important and should be paid more attention. Yeomans [3] says that good practices, such as the correct positioning of the reinforcing bars in the moulds and the assuring of a right pouring, compaction and curing of the concrete structures would be enough to ease the corrosion problems. However, due to the perceivable deficiencies in Brazilian construction processes, it is still frequent the appeal for techniques that improve the concrete/reinforcement bars interface.

Among the most used techniques, the application of galvanic coatings with metals more noble than steel in the reinforcing bars has a special place. The zinc (Zn) is the metal more frequently used in these coatings [3], mainly because of its ability to create a dense and adherent protective film on the bar surface, causing the corrosion rates to become lower than the ones observed in ferrous materials.

It is also common to add other components to the Zinc coating, such as cobalt (Co), iron (Fe) and nickel (Ni), forming the alloys Zn-Co, Zn-Fe and Zn-Ni, which present better properties when compared to the pure Zinc coatings. In this context, the compounds based in Zn-Ni are drawing more interest regarding the protection against corrosion due to the presenting of superior chemical and mechanical properties [4].

There are two main methods to make the Zinc protective layer: hot dip galvanizing and electroplating. In the first one, the steel bar is immersed in molten Zinc, while in the second one ions of a more noble metal are deposited on the substrate due to the application of an electric current. This last method is a quite common process in the industry, producing a layer that is extremely thin and relatively free of pores, avoiding material waste [5-7]. The thickness of the coating is influenced by some factors, for instance the current density, the salt concentration, the bath temperature, the presence of additives and the nature of the base metal [8]. Furthermore, the electroplating method does not generate intermetallic alloys like the hot dip galvanizing method, providing a more homogenous and thin coating that will not affect mechanic properties of its substrate [9].

There are various techniques to evaluate and assess the corrosion, and among the most used ones we have the electrochemical techniques, which can be used both in field and inside a laboratory. More specifically, the assessment of the potential of corrosion is one of the electrochemical techniques that allows us to record the changes in the electrochemical process of corrosion (due to the considerable variation in the potential), what ends up being a very interesting way to monitor reinforced concrete structures. However, the values measured by this method indicate only the balance between the anodic and cathodic reactions, not offering any information regarding the real velocity of the bars corrosion [10].

Nevertheless, the assessment of the corrosion potential enables the mapping of the regions of the reinforced concrete structure where the corrosion process has begun. Due to this, its application is becoming more and more frequent [4]. Based on reference values provided by the United States standard ASTM C-876/91 ("Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete"), it is possible to have an idea of the corrosion process situation.

The mentioned standard informs the potential reference ranges regarding the type of electrodes used to gather the values. According to the table 1, for the calomel electrode, which was used in this research, it is given the range of values where there is a probability of less than 10% of occurrence of corrosion, thus indicating a passive state (E_{corr} > -0.124 V), an unsureness of corrosion state (-0.124 > E_{corr} > -0.247 V), and a probability higher than 90% of corrosion occurrence (E_{corr} < -0.247 V).

It is important to remember that the standard provides guidelines for the analysis of reinforcing bars made of steel only, without any type of coating. Since the interpretation of the results from the electrochemical procedures will be influenced by the change in the potentials of Zinc, Zinc-Nickel and steel, it is fundamental to know how to interpret these Zinc and Zn-Ni values, because the standard corrosion and passivation ranges do not suit them [4].

As it was observed before by Sherine et al. [11] and Panek et al.[12], when steel is electroplated with Zinc, its potential of corrosion regarding the saturated calomel electrode gets lower values to indicate high probability of corrosion, that is below -1.043 V, and passivation state, which is above -0.650 V. Still according to Panek et al. [12], the potential of corrosion that indicates high probability of corrosion of the steel electroplated with a Zinc-Nickel alloy is

Table 1 – Probability of corrosion of the steel bars according to its potential for each electrode

Type of eletrode	Probability of corrosion occurence		
	< 10%	10% - 90%	> 90%
SHE*	> 0,118 V	0.118 V to -0.032 V	< -0.032
$Cu/CuSO_4,Cu^{2+}$ (ASTM C876)	> -0.200 V	-0.200 V to -0.350 V	< -0.350
$Hg,Hg_2Cl_2/KCl$ (saturated sol.)**	> -0.124 V	-0.124 V to -0.274 V	< -0.274
Ag,AgCl/KCl (1M)	> -0.104 V	-0.104 V to -0.254 V	< -0.254

* Standard Hydrogen Electrode; ** Saturated Calomel Electrode, used in this research.

Table 2 – Potential of corrosion zones indicating the high probabilities of corrosion or passivation according with the surface condition (using as reference the SCE)

Surface condition	Potential that indicates passivation (V)	Potential that indicates corrosion (V)
Conventional steel bar	> -0.124	< -0.274
Electroplated with Zn	> -0.650	< -1.043
Electroplated with Zn-Ni (5%)	> -0.550	< -0.953

below -0.953 V, and its passivation potential would be -0.550 V. These values were adopted as parameters to interpret the readings of corrosion potential found in the bars galvanized with Zinc and Zinc-Nickel alloy, respectively, as it can be seen in the table 2. This research aims to study the influence of the Zinc and Zinc-Nickel electroplating galvanization in the corrosibility of the reinforcing bars embedded in the concrete. In order to make this slow process possible to be fully studied in a short time scale, the reinforced concrete specimens were subjected to accelerated corrosion test, being monitored by the electrochemical technique of the potential of corrosion and in the end they had the rate of corrosion of theirs reinforcing bars estimated by the loss of mass measured in each bar.

2. Materials and methods

2.1 Materials

In this research, it was used the Portland cement CP II Z-32, brand Poty. The crushed stone used is of basaltic origin, while the sand is commercialized in the metropolitan region of Salvador-BA. The steel bars used belong to the CA 50-A class (Brazilian Standard) and have a 6.3mm diameter.

2.2 Methods

2.2.1 Characterization of the raw materials and concrete dosage

The Portland cement characterization covered parameters such as specific surface area (SSA), which was estimated by BET using a Micrometrics Gemini 2370 V1.02), density, using a Helium Pycnometer Accupyc 1330 V2.01 from Micrometrics), and the particle-size distribution (PSD), using a laser sedigraph Mastersizer 2000. The sand and the crushed stone had their granulometry obtained following the Brazilian standard NBR NM 248:2003, and so it was to their fineness module and Maximum aggregate size as well. The sand density was determined by following the Brazilian standard NBR NM 52:2009, while the crushed stone density followed instructions of the NBR NM 53:2009. The density of the cement used the Le Chatelier's bottle method, according to the NBR NM 23:2001.

The concrete mixing ratio adopted in this research was 1.0:1.5:1.3:0.5 (cement, sand, crushed stone, water), based in RIBEIRO et al. [14] studies, that used the dosage method proposed by ACI (*American Concrete Institute*). The mortar content was of 70% and the cement consumption was of 534 kg/m^3. After mixing, a vibrating table was used to ensure efficient compaction. Then, the concrete specimens with different types of embedded bars (conventional and with Zinc and Zinc-Nickel coatings) were manufactured and subjected to the tests. The fundamental characteristics of the concrete, as well as their materials consumption per cubic meter are shown in Table 3.

For the potential of corrosion measurements, it was made prismatic specimens (50x70x90 mm^3) in which were embedded the bars with the diameter of 6.3mm. These bars were fixed in the mould waiting for the concrete to be poured. All specimens rested for 24 hours and then were taken off the moulds to go to the curing process for 28 days. A minimum of four specimens were tested for each type of electrodeposited coatings, as well as reference specimens.

2.2.2 Concrete characterization

The concrete used for the preparation of the samples was

Table 3 – Materials consumption and fundamental characteristics of the concrete

Proportion (cement : dust : crushed stone : water)		1.0 : 1.5 : 1.3 : 0.5
Materials consumption	Cement (kg/m^3)	534
	Dust (kg/m^3)	801
	Crushed stone (kg/m^3)	694
	Water (kg/m^3)	267
Fundamental characteristics of the concrete	Water/cement ratio	0,5
	Dry mortar (%)	58,1
	Water/Dry materials ratio (%)	13,2
	Slump (mm)	220

Table 4 – Composition of the electrolyte solution used for zinc electroplating

Zinc solution (g/L)	
Potassium choride	208.0
Zinc chloride	19.6
Boric acid	20.0

characterized as to its fundamental properties: workability (slump test), apparent porosity and density, capillary water absorption and resistance to axial compression.

The workability of the concrete was evaluated by the slump test method, according to Brazilian NBR NM 67: 1998 standard ABNT NBR. The apparent porosity and density were verified using the technique based on the Archimedes principle. The samples were weighed while they were still dry (Ms). They were then left immersed in water for 24 h until they became fully saturated, after which the immersed mass (Mi) and the wet mass (Mu) were determined. Thus, the apparent porosity (PA) and the apparent density (D_A) were calculated according to equations (1) and (2)

$$\%P_A = 100.\frac{Mu - Ms}{Mu - Mi} \quad (1)$$

$$D_A = \rho_L.\frac{Ms}{Mu - Mi} \quad (2)$$

Table 5 – Composition of the electrolyte solution used for zinc-nickel alloy electroplating

Zinc-10% Nickel Solution (g/L)	
Nickel chloride	34.5
Ammonium chloride	150.0
Zinc chloride	38.5
Boric acid	20.0

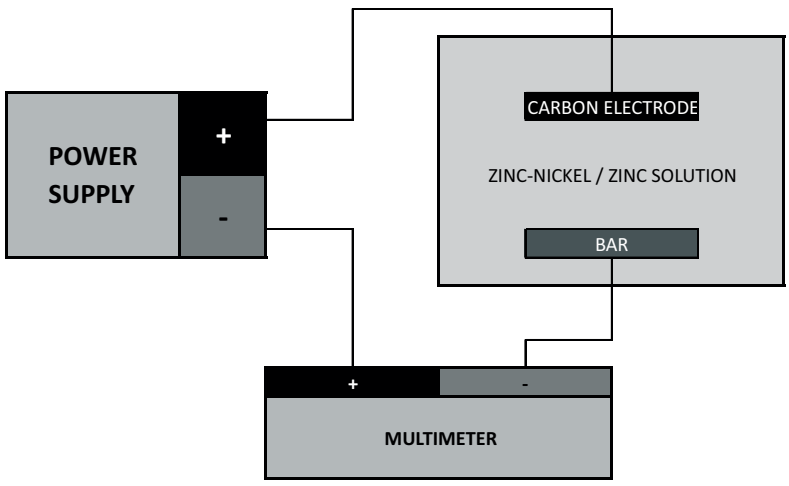
The ρ_L is the liquid density (in this case, the water, ρ_L = 1.0 g/cm³ at 25ºC). The specimens used in the test, in a number total of five, all had 28 days of age.

Checking the water absorption by capillary of the mortar is very important because excessive absorption of water is an indicator of a greater diffusion of elements and solutions to the interior of the material which, consequently, increases the chances of occurrence of rebar corrosion.

The specimens used in the test, in a number total of 3, all had 28 days of age. The procedure was carried out according to the NBR 9779 standard. The capillary absorption coefficient is thus estimated, which represents the weight of water absorbed by square meter of mortar in contact with water according to the square root of time to reach this level of absorption. Numerically, this value corresponds to the slope of the plot straight from the "absorption ($kg.m^{-2}$) x square root of time ($minutes^{0.5}$)" graph until it reached the point of saturation, according to equation 3.

$$A = S.\sqrt{t} \quad (3)$$

Figure 1 – Representation of electric circuit used for the bars electroplating



The values of axial compression correspond to the average of three values obtained 28 days after molding, and were obtained with an Contenco HD-120T testing machine and a load of 1.5 mm/min. The specimens that presented an error of more than 5% were excluded and replaced by others, following the procedure established by the Brazilian NBR 5739:2007 standard.

2.2.3 Zinc and zinc nickel electroplating

The galvanization process chosen in this research was the electroplating one. It was assembled an electric circuit for the Zinc or Zinc Nickel electrolytes of the electrolyte solution to be deposited on the steel bar due to an electric current applied. The compositions of these two solutions, proposed by PEDROZA [18] studies, are presented in the tables 4 and 5.

Before the electroplating process, the bars were cleaned with an iron brush and then bathed with distilled water and ethylic alcohol in order to remove any speck that would stick onto its surface, assuring the efficiency of the deposition.

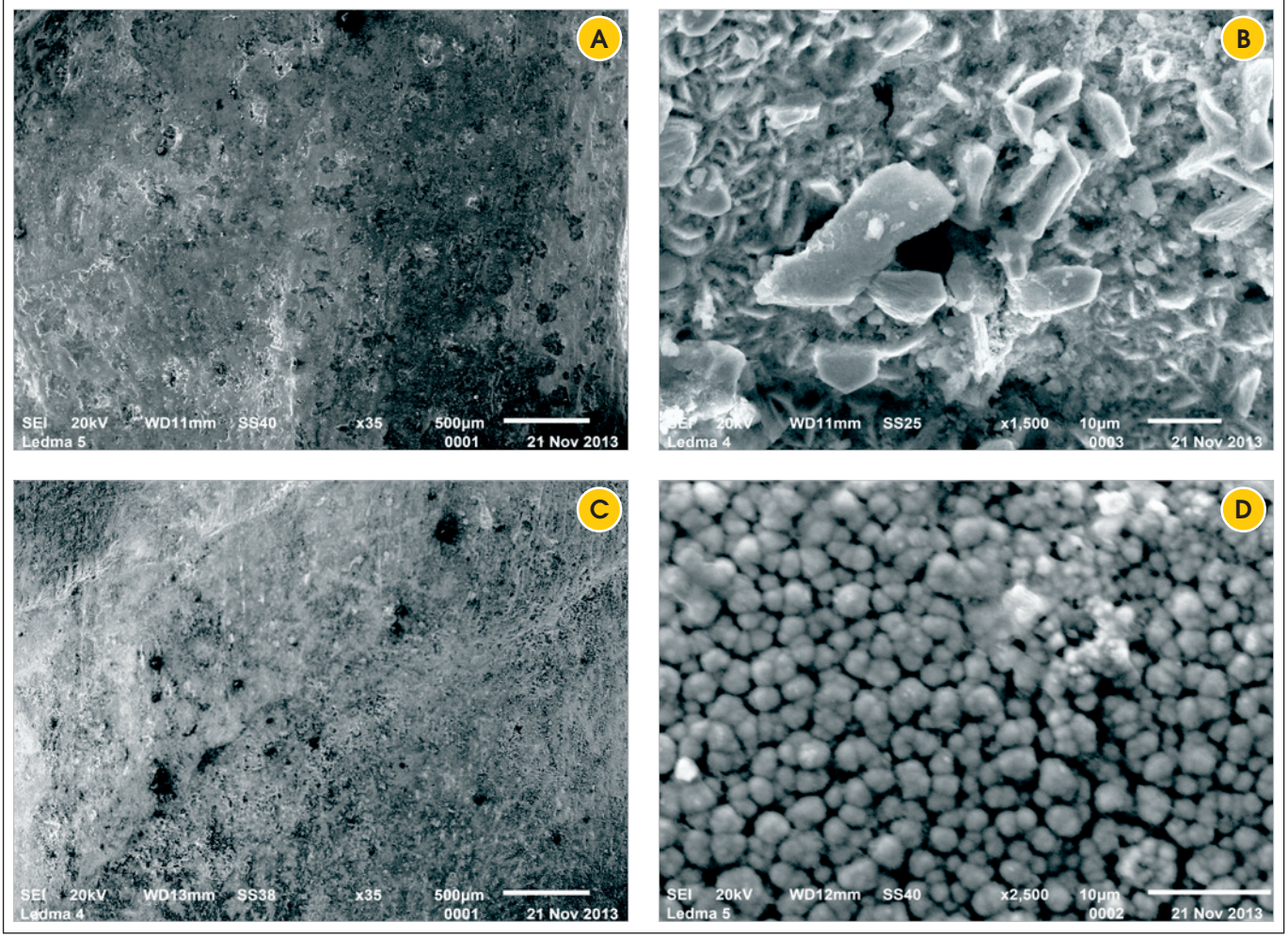
Besides the bars to be coated, the assembled circuit comprises a power supply and a carbon electrode, which was also immersed into the electrolyte solution to close the circuit. A multimeter was a component of the circuit as well so the current could be double checked. The circuit can be seen in figure 1.

Unlike the hot dip galvanizing process, which deposits thicker layers, above 80 μm [4, 19] and in accordance with ASTM A767-09:05 standard (*Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*), a typical coating of zinc obtained by electrodeposition does not exceed 20 micrometers. In this study, a cover thickness of 5μm was used, in order to obtain comparative results and verify the effectiveness of coatings , even with layers of small thickness .

Aiming to achieve a 5μm thickness coating, it was calculated the current value of 314.6 mA. The duration of the immersion was also calculated to be 9 and 8 minutes for the Zinc and Zinc-Nickel coatings respectively.

According to the microphotographs showed in Figure 2, the obtained coatings presented an uniform distribution of the

Figure 2 – Microphotographs of the bars surface after the Zinc (A and B) and Zinc-Nickel Alloy (C and D) bars electroplating process



electrodeposited ions, creating a homogeneous layer in each case, but with different morphologies for each case. While the Zinc coating exhibited a surface formed by flat grains randomly scattered and of various sizes, the Zinc-Nickel coating presented spherical same sized grains distributed all over the surface, as it was previously observed in other researches [6,13].

2.2.4 Potential of corrosion measurement

The steel bars were weighted by an analytic scale with 0.01g of accuracy. Then, it was used a tape to mark the area that would be exposed to the attack of the aggressive agent (around 15.8 cm^3), as it can be seen in Figures 3a and 3b. These bars were fixed in a way that these areas would be at the centre of the concrete specimens, as showed in the Figure 3d.

The verification of the corrosion potential happens along the test of accelerated chloride induced corrosion. The electrochemical cell used in these tests was formed by two electrodes, one of them being the steel bar embedded in the concrete specimen (coated or not) and the other one was the saturated calomel electrode, to be used as reference.

Before performing the measurements, the specimens had their reading side wetted by placing a wet sponge on it during 1 minute. This wet sponge was soaked with an electric conducting solution, which was made according to the United States standard ASTM C-876/91 ("Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete"), having 5ml of a neutral detergent for 1 litre of water and presenting a conductivity of 0.15 ± 0.02 mS/cm. Finally, the readings demand the SCE to be placed touching the sponge at the middle of the specimen side, as it is shown in the figure 4.

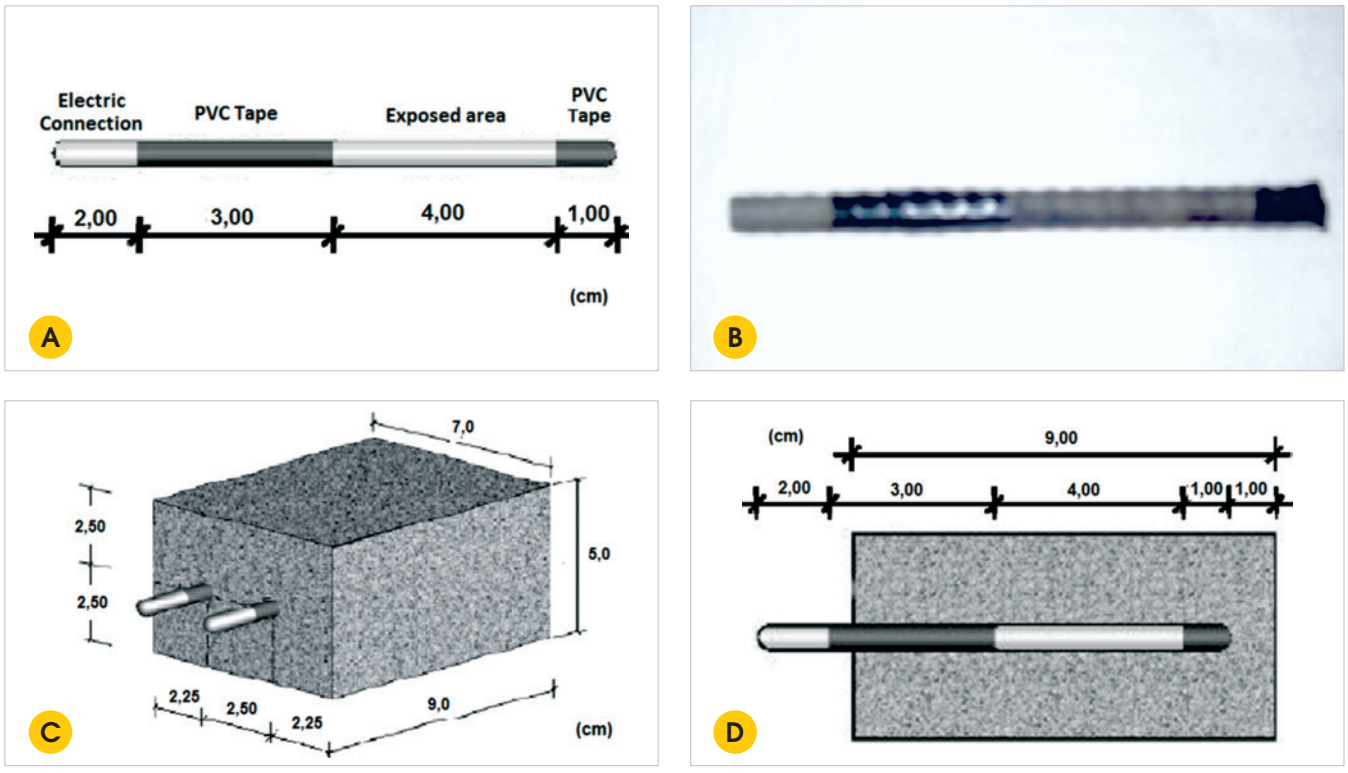
The corrosion tests started after 63 days curing, when the specimens presented weight constant (which means that they all had a weight variation of less than 1.0g in 24 hours) and when the potential of corrosion pointed to the formation of a passive layer on the surface of the steel bars (E_{corr} > -0.124 V, for the conventional bars; E_{corr} > -0.650 V, for zinc coated bars; and E_{corr} > -0.550 V, for zinc-nickel coated bars). These values indicate that there is a probability of less than 10% for the corrosion to occur using the SCE and are based on the US standard ASTM C 876/91. They also indicate the formation of this oxide passive film.

In other researches [14-16], it was considered necessary to define a specific age when to start the accelerated corrosion tests. These authors related this specific age to the stabilization of the concrete hydration process, defining 63 days [14, 16] and 80 days [15] as the amount of time needed for the concrete micro structure to present a good development and a satisfactory hydration level.

After reaching the potential that indicates passivation, the specimens were divided in two groups and each one was subjected to an accelerated corrosion process: i) aging cycles of half-immersion and drying, ii) Salt spray exposure.

In the first process, the specimens were half immersed in a solution containing 3% of sodium chloride (NaCl) for 2 days and then are moved to a laboratory oven at 50°C for 5 days. During the first

Figure 3 – (A) and (B) Scheme of delimitation of the bars exposed area; (C) and (D) Position of bars inside the concrete specimen (adapted from SANTOS (11))



half-cycle, the solution level is kept at the middle of the bar exposed area inside de concrete specimen. In this condition, the chloride penetration happens firstly due to the capillary absorption, since the concrete samples are initially dry, and then due to diffusion when the pores are completely saturated, being accelerated by the water evaporation that takes place in the non-immersed area of the specimens. According to MC-CARTER apud SANTOS [11], there is a relation between the saturation level and the capillary suction forces in a porous material. Thus when there is a dry and exposed region, these suction forces will be greater, pulling faster the solution into the concrete specimen.

The 3% NaCl concentration was adopted because of its similarity with the sea water concentration. That was checked before starting the half-immersed part of the aging cycles and corrected if necessary. Besides, the NaCl solution was changed after 4 cycles.

At the end of each part of the cycle, the potential of corrosion (E_{corr}) was measured along with the weight of the specimens. The potential measurements were to probe what was the condition of the bars regarding its passivation/corrosion state, while the weighting was to verify its saturation level.

Through the analysis of the corrosion potential results, it was observed if the bar were in passive or active state of corrosion, using for this the values referred to the SCE. This test was ended when two consecutive cycles would give potential below the one that indicates high probability of corrosion.

For its turn, in the salt spray test the concrete specimens were place inside a salt spray chamber (Equilam SS600e) under conditions stablished by the ASTM B-117 (“Standard Practice for Operating Salt Spray (Fog) Apparatus”). As oriented by the standard, the saline solutions must have a NaCl concentration of 5%, its pH must stay between 6.5 and 7.2 and the inner temperature to be kept at 35°C. Periodical measurements of the potential of corrosion were performed in order to verify how the corrosion process was.

After the ending of both tests, the bars were extracted from the specimens, cleaned following the orientations of the ASTM G-1/03 and then weighted so the loss of mass could be found by comparing with the weight of them before embedding them in the specimens. Then, the corrosion rate (CR) was calculated following the equation 4.

$$CR = \frac{K.W}{A.T.D} \quad (4)$$

Where K = constant (for CR in μm/year, K=8.76 x 10^7; for CR in g/m².year, K = 8.76 x 10^7.D); W = loss of mass (g); A = exposed area (cm²); T = duration of exposure (h); D = density (for CA-50 steel, D = 7.85 g/cm³). In this research, A = 15.83 cm² e T = Time that the tests lasted.

3. Results and discussion

3.1 Materials characterization

The Portland cement used in this research presented a specific surface area of 0.425 m²/g and its density was of 2.98 Kg/dm³. The sand density was of 2.63 Kg/dm³, and its fineness Modulus 1.52, being classified as fine sand. The crushed stone obtained a density of 2,79 Kg/dm³ and its maximum aggregate size was of 9.5 mm and classified as “stone 0”. The granulometric distributions can be seen at the figure 5.

Figure 4 – Measurement of the potential of corrosion being performed (14)

3.2 Concrete characterization

The concrete used for the preparation of the samples was characterized as to its fundamental properties: workability (slump test), apparent porosity and density, capillary water absorption and resistance to axial compression. The results are presented in Table 6.

3.3 Corrosion Potential

The corrosion potential of the bars subjected to the wetting-drying aging cycle was assessed in the end of each immersion and drying phase and can be seen in the Figure 6.

During the test, the observed potential values behaved as expected and noted in previous related works [14], as the measures

Table 6 – Concrete characterization

Proportion (cement : dust : crushed stone : water)		1.0 : 1.5 : 1.3 : 0.5
Characteristic	Result	Standard
Slump	220 mm	NBR NM 67:1998
Apparent porosity	(18.25 ± 0.45) %	NBR 9778:2009
Apparent density	(2.15 ± 0.09) g/cm^3	NBR 9778:2009
Capillary water absorption	(0.129 ± 0.019) kg/m^2.min^{0,5}	NBR 9779:2012
Axial compression resistance	(31.1 ± 0.72) MPa	NBR 5739:2007

taken in the wetting cycle were much lower than the measures of the drying cycle. This fact is explained by ROCHA [17] that shows that temperature, humidity and saturation level directly interfere in the electrochemical measures of the potential of corrosion, and that interference is boosted by the chloride contamination.

In the salt spray exposure test (SSET), the parameters cited before (temperature, humidity, saturation level) are kept constant, causing a different behaviour in the potential of corrosion readings, as can be seen at the figure 7.

As suggested by GONZÁLEZ et al. [18], the measures of the potential are not conclusive by themselves due to the variety of factors that affect it, giving only preliminary indicatives of the bars corrosion situation. As it can be seen, the potential of corrosion of the coated bars stayed in the uncertainty range (E_{corr} > -1,043 V, for bars coated with Zinc and E_{corr} > -0,953 V, for bars coated with Zinc-Nickel), while the bars with no coating presented potentials in the high corrosion probability range (E_{corr} < -0,274 V). Such behaviour indicates that there is a protective effect over the reinforcing bars regarding their despassivation when they are coated with Zinc or the Zinc-Nickel alloy by electroplating process, what is due the delay in the change from passive to active state of corrosion. However, as the corrosion potential is just a qualitative test, it does not allow the coatings to be compared regarding their protection efficiency.

3.4 Corrosion rate

The loss of mass observed in the bars after the tests of accelerated corrosion allowed the average corrosion rates to be estimated for each group of bars (coated with Zinc, Zinc-Nickel and uncoated), as shown in figures 8 and 9. As expected, in both tests the galvanized bars presented a lower corrosion rate than the uncoated ones.

In the aging cycles test, the uncoated bars shower a corrosion rate (250,40 µm/year) much higher than the galvanized with Zinc (167,49 µm/year) and Zinc-Nickel (166,15 µm/year). These results mean a decrease of 33.1% and 33.6% respectively in the corrosion rates when the average values of each group are compared, causing the galvanized bars to have a better durability. It was also possible to notice that the Zinc-Nickel coating presented the best results regarding the corrosion rate, with the lowest discrepancies, which is in agreement with the more uniform aspect of the Zinc-Nickel distribution on the surface of the steel bar.

It is important to highlight that the adopted thickness (5 µm) of both coatings may have influenced in the high deviation of the results, given that usual coating thicknesses are far greater (around 100 µm). It may also have contributed for a poor formation of the zinc oxides layer that would delay the corrosion process. Besides, it is possible that some local flaws in the coatings would provoke corrosion type different from uniform corrosion, which is the one assumed for the calculation of the corrosion rate.

The results obtained from the salt spray exposure tests (SSET) (figure 6) showed much less variability, and a smaller order of magnitude, what indicates this test to be less aggressive than the aging cycles test. It was found a corrosion rate of 22.50 µm/year for uncoated bars, 15.58 µm/year for zinc coated bars, and 15.40 µm/year for zinc-nickel coated bars. One more time it is indicated the increase of the life cycle of coated bars.

Figure 5 – Particle size distribution and classification limits of the (A) dust (inferior limit) and (B) crushed stone (4,75-12,5 mm, stone 0), used to concrete production

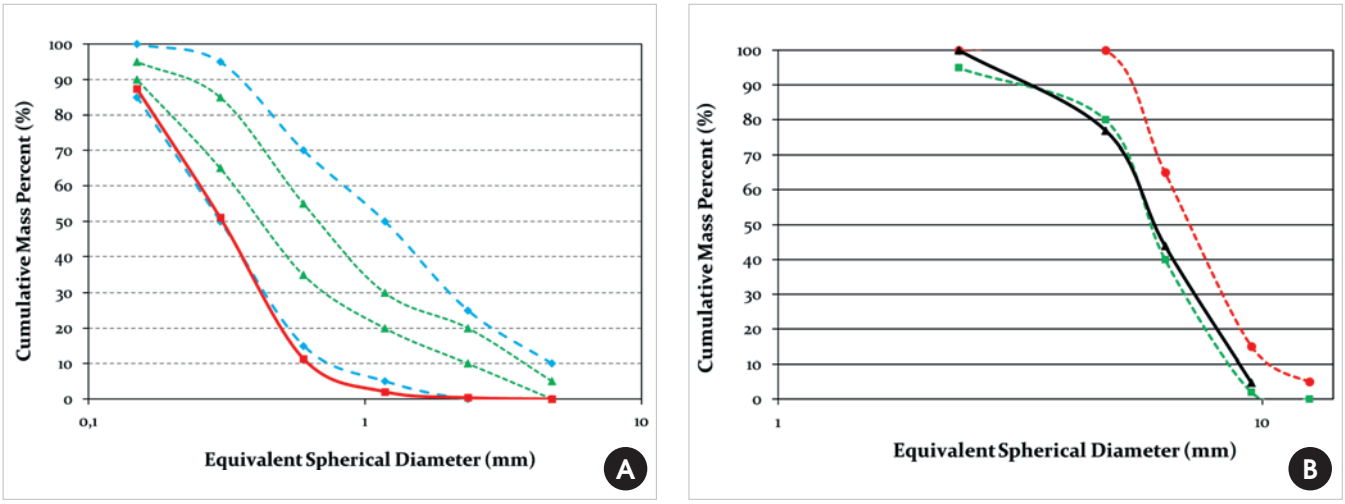
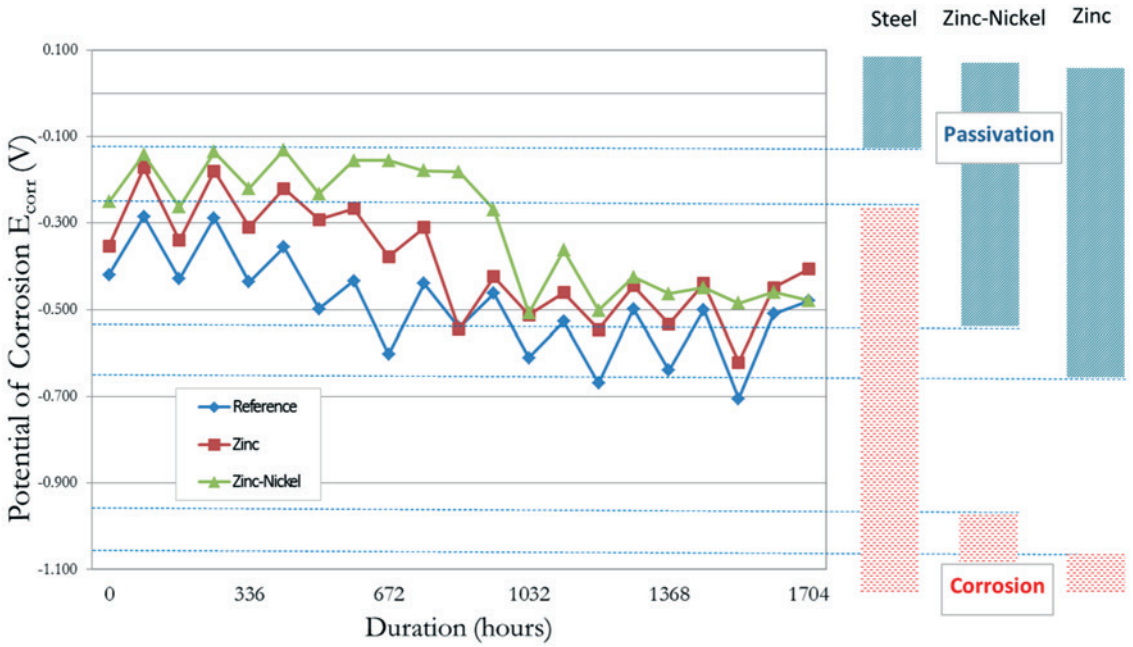


Figure 6 – Evolution of the potential of corrosion during the aging cycles test for the conventional and coated bars



Still, it was possible to compare the efficiency of the accelerated corrosion tests through the analysis of the corrosion rate. While the uncoated bars presented a rate of 250.40 µm/year in the aging cycles test, in the salt spray chamber process the average rate was of 22.50 µm/year. The same occurs for the coated bars, where to the first test was found corrosion rates of 167.49 µm/year (Zinc) and 166.40 µm/year, while in the salt spray test was found rates of 15.58 µm/year and 15.40 µm/year, respectively. That shows that the test at which the corrosion is accelerated by the cycles of wetting and drying is more efficient for the evaluation of corrosion in reinforced concrete specimens.

Such difference may be explained by the scarcity of one of the indispensable components for the corrosion process: oxygen. Since the salt spray chamber is airtight sealed and the specimens are saturated most of the time, the oxygen entrance in the specimen becomes less effective. Therefore, some alterations in the test that

Figure 7 – Evolution of the potential of corrosion during the salt spray exposure test for the conventional and coated bars

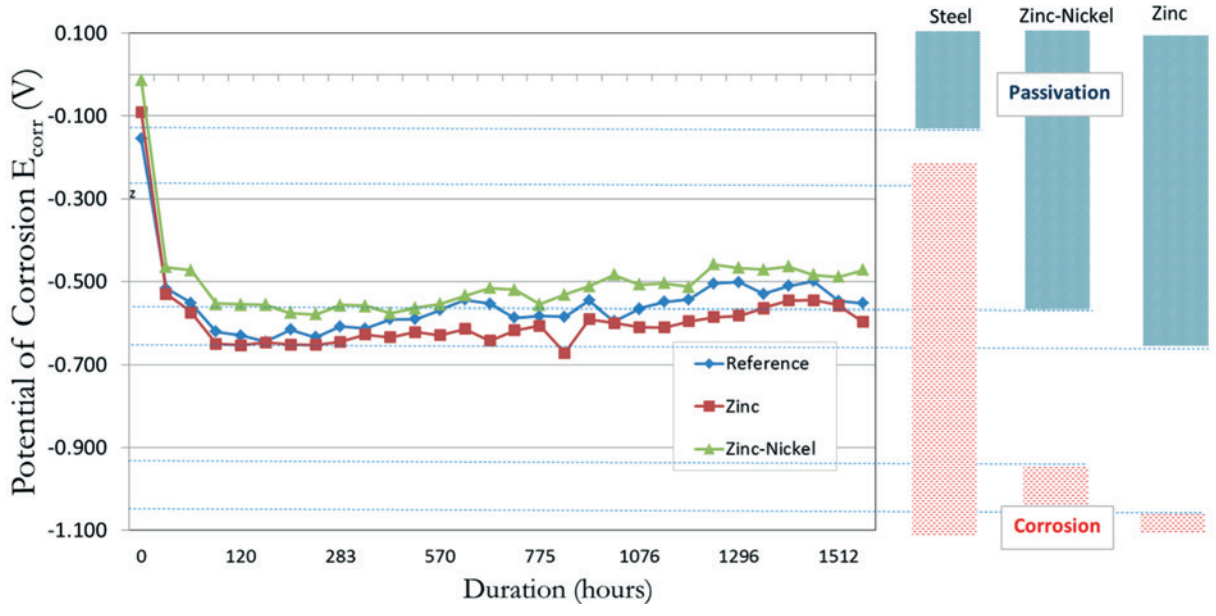


Figure 8 – Corrosion rates for the conventional and coated bars after the ACT

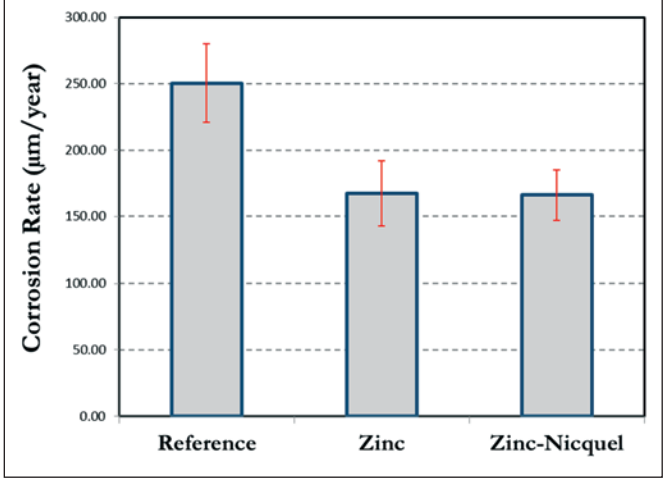
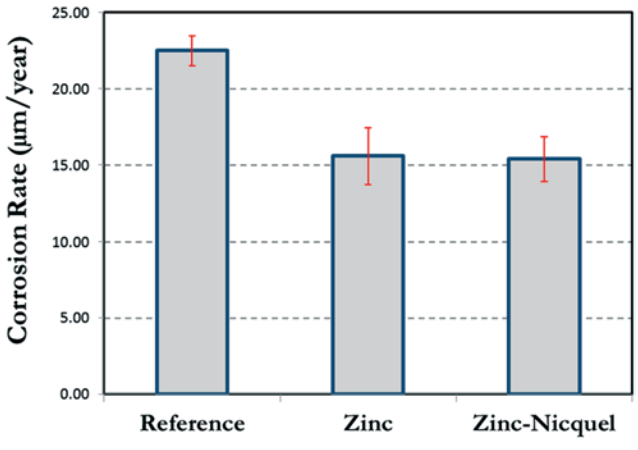


Figure 9 – Corrosion rates for the conventional and coated bars after the SSET



would allow more oxygen to come in may cause it to better accelerate the corrosion in the reinforced concrete specimens.

4. Conclusions

From the results that were found, it was possible to conclude that:

- The galvanization by electroplating is an efficient protective method for the reinforcing steel bars in the civil construction;
- The Zinc and Zinc-Nickel coatings proved themselves to be effective as to increase the life cycle of reinforcing bars, although the thickness adopted in this research might not have been enough to promote a substantial increasing in the life cycle, since this thickness might have interfered in the coatings performance;
- The accelerated corrosion test of wetting and drying cycles proved to be more effective to evaluate the corrosion process in the reinforced concrete specimens when compared with the salt spray exposure test (SSET);
- The utilization of more refined monitoring techniques is necessary to achieve a better understanding of how works the coatings of zinc and zinc-nickel alloy in the reinforced concrete, since the literature about it is rather scarce.

5. Acknowledgements

To the Pró-Reitoria de Ensino e Pós-Graduação (PROPG) and to the Pró-Reitoria de Pesquisa, Criação e Inovação (PROPCI) for the research scholarship. To all group from LEDMA, LAMET and CETA for the support.

6. References

[1] GENTIL, V. Corrosão, Rio de Janeiro: LTC, 5ed, 2007.

[2] CALLISTER, Jr., W.D. Ciência e engenharia de materiais: Uma introdução, Rio de Janeiro: LTC, 7ed, 2008.

[3] YEOMANS, S. R. (Ed.) Galvanized Steel Reinforcement in Concrete. [Camberra]: Elsevier, 2004. cap. 6.

[4] BROOMFIELD, J. P. Galvanized Steel Reinforcement in Concrete: A Consultant's Perspective In: YEOMANS, S. R. (Ed.) Galvanized Steel Reinforcement in Concrete. [Camberra]: Elsevier, 2004. cap. 9.

[5] GRAVILA, M.; MILLET, J.P.; MAZILLE, H.; MARCHANDISE, D.; CUNTZ, J.M. Corrosion behaviour of zinc-nickel coatings, electrodeposited on steel. Surface and Coatings Technology v.123, 1999; p164-172.

[6] GHAZIOF, S.; GAO, W. Electrodeposition of single gamma phased Zn-Ni alloy coatings from additive-free acidic bath. Applied Surface Science v.311, 2014; p635-642.

[7] WILCOX, G. D.; GABE, D. R. Electrodeposited zinc alloy coatings, Corrosion Science 35 (5-8) (1993) 1251-1258.

[8] PEDROZA, G. A. G. Efeito da Glicerina como aditivo na Resistência à Corrosão de um Depósito da Liga Zn-Ni, obtido através de Eletrodeposição, Salvador, 2009, Dissertação (mestrado), Escola Politécnica, Universidade Federal da Bahia, 112p.

[9] ZEMPULSKI, L. N.; ZEMPULSKI, M. F. S. Dossiê técnico: galvanização eletrolítica. Instituto de Tecnologia do Paraná TECPAR, 2007, p.21.

[10] FREIRE, K. R. R. Avaliação do desempenho de inibidores de corrosão em armaduras de concreto, Curitiba, 2005, Dissertação (mestrado), Universidade Federal do Paraná.

[11] SHERINE H. B.; RAJAKUMARI C. C.; RAJENDRAN S. Corrosion behaviour of stainless steel 304 electroplated with zinc followed by blue passivation. Portugaliae Electrochimica Acta, v.29, n.4, 2011; p.295-305.

[12] PANEK, J.; BIERSKA-PIECH, B.; KAROLUS, M. The corrosion resistance of zinc-nickel composite coatings, Journal of Achievements in Materials and Manufacturing Engineering Katowice, v.45, n.2, 2011; p.157-162.

[13] RAMANAUSKAS, R.; QUINTANA, P.; MALDONADO, L.; POMÉS, R.;PECH-CANUL, M. A. Corrosion resistance and microstructure of electrodeposited Zn and Zn alloy coatings, Surface and Coatings Technology 92 (1-2) (1997) 16-21.

[14] RIBEIRO D. V.; LABRINCHA J. A.; MORELLI M. R. Effect of the addition of red mud on the corrosion parameters of reinforced concrete. Cement and Concrete Research, v. 42, 2012; p.124-133.

[15] SANTOS, L. Avaliação da resistividade elétrica do concreto como parâmetro para a previsão da iniciação da corrosão induzida por cloretos em estruturas de concreto, Brasília, 2006, Dissertação (mestrado), Universidade de Brasília, 161p.

[16] BAUER, E. Avaliação comparativa da influência da adição de escória de alto-forno na corrosão das armaduras através de técnicas eletroquímicas, São Paulo, 1995, Tese (doutorado), Escola Politécnica, Universidade de São Paulo, 236p.

[17] ROCHA, F. C. da. Leituras de potencial de corrosão em estruturas de concreto armado: influência da relação água/cimento, da temperatura, da contaminação por cloretos, da espessura de cobrimento e do teor de umidade do concreto, Curitiba, 2012, Dissertação (mestrado), Universidade Federal da Paraná.

[18] GONZÁLEZ, J. A.; MIRANDA, J. M.; FELIU, S. Considerations on reproducibility of potential and corrosion rate measurements in reinforced concrete. Corrosion Science, v.46, p.2467-2485, 2004.

[19] ABDALA, L.; ALBAGLI, D. Vergalhão Galvanizado: Vantagens, Aplicações e Desempenho em Estruturas de Concreto Armado. In: VII Congresso Brasileiro de Pontes e Estruturas, Rio de Janeiro, p. 1-10, 2014.