

## EVALUATION OF TECHNIQUES FOR THE PREVENTION OF STEEL CORROSION IN REINFORCED CONCRETE IN AN AGGRESSIVE ENVIRONMENT

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### Abstract:

The purpose of this study was to evaluate the influence of cement type, concrete cover, and addition of migratory corrosion inhibitor (MCI) on the corrosion resistance of reinforced concrete subjected to an aggressive environment. For this, corrosion tests were performed using CP IV RS and CP II F types of cement with two levels of concrete cover: 2.5 cm and 4 cm. In the thinner one, the migrating corrosion inhibitor was added. In the research the techniques used were the determination of concrete compressive strength, electrode potential measurements, acceleration cycles of chloride attack, and visual analysis. The results showed that both the cement type and the migratory corrosion inhibitor contributed to the inhibition of steel corrosion. In concretes with inhibitor and thinner cover the most extreme measurements were verified: in the 14<sup>th</sup> weekly cycle the concrete with CP II F cement presented a potential of -366 mV, characterizing a 90% of probability of corrosion, while the one with CP IV RS showed a potential of -119 mV, with a corrosion probability of less than 10%. However, following the cycles, it was possible to identify an increase in the value of this potential. The influence of the concrete cover thickness was also observed since the potential values found were more negative in the cases of smaller covers.

### Keywords:

Corrosion of steel; reinforced concrete; electrode potential measurements; migratory corrosion inhibitor; thickness of cover; cement type.

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## INTRODUCTION

Due to exposure to the environment, reinforced concrete structures, over time, are susceptible to compromising their stability and functionality. Reinforced concrete is seen as the main material used in construction, considering its elementary composition of great durability. With the evolution of calculation methods, the greater use of technology in construction, and the improvement of building systems, there has been an increase in productivity, a reduction in costs, and the execution of slender structures. However, such factors have also caused the reduction of concrete covering for the steel reinforcement and the increase of work stresses and risks of degradation, consequently influencing the service life of buildings (Ribeiro, 2014).

One of the main factors to be considered when designing reinforced concrete structures is the local atmosphere. In aggressive environments, such as coasting areas, the corrosion of reinforcement is of particular concern: the exposure conditions are favorable to the entry of contaminated fluids, mainly by chloride ions, through the pore network of the concrete cover (Bertolini, 2010).

According to Sousa (2014), corrosion can be defined as a process of material deterioration due to the chemical or electrochemical action of the environment. In addition to influencing the mechanical properties of the steel reinforcement, corrosion can result in the formation of a bulky product which, by pressing the concrete cover, can cause the spalling of the layer (El-Reedy, 2018; Bertolini *et al.*, 2013). In general, corrosion of reinforced concrete results in significant additional costs, either to replace corroded material or as a consequence of indirect losses, such as the need for corrective maintenance, the use of more corrosive resistant materials, or losses due to downtime of the use of the building. Reinforcement cover thickness and concrete quality are considered extremely important factors in avoiding corrosion and prioritizing the durability of structures (ABNT, 2014).

According to Helene (1993), corrosion stands out as one of the main causes of early deterioration of reinforced concrete structures, reducing, in many cases, the service life of constructions. Its consequences imply various aspects related to structural conditions, such as aesthetics, ease of maintenance, safety, and structural performance, and usually manifest through the cracking of the concrete cover (Bertolini *et al.*, 2013). Most cases of corrosion and degradation of concrete are consequences of electrochemical reactions initiated by the presence of chloride ions (Mehta & Monteiro, 2014). Upon contact with the surface of the structure, the chloride ion can diffuse through the concrete pores and reach the reinforcement in a shorter time than expected for the service life. In concretes containing significant concentrations of chloride ions, the passive

protective film of the steel may break, propagating corrosion (Cascudo, 1997).

Different types of Portland cement are sold in Brazil. They have different chemical and physical compositions due to the inclusion of mineral additions in their fabrication, resulting in a disparity in the properties of the mixtures produced with them (Medeiros-Junior *et al.*, 2014). According to Neville (2016), types of cement containing mineral additions, such as slag or pozzolan, have a greater ability to restrict the mobility of aggressive ions within the matrix, as they reduce the permeability of concrete, by reducing the pores of hardened cement paste, increasing its electrical resistivity (Andrade & D'Andrea, 2011). Thus, the type of cement used directly influences the durability of reinforced concrete structures, which may reduce the occurrence of corrosion according to the additions it receives (Mather, 2004).

The concrete cover is the first line of defense to protect steel reinforcement from corrosion (El-Reedy, 2018) and is determined according to the type and level of environmental aggressiveness predicted in the project (ABNT, 2014). According to Verma *et al.* (2013) and Zhou *et al.* (2015), the corrosion rate of steel decreases as the thickness of the concrete cover increases. In accordance with Helene (1993), such thickness directly influences the speed of the corrosion process, which occurs due to the greater or lesser mobility of aggressive ions through concrete to steel. The study by Rocha *et al.* (2014) confirms the importance of the concrete cover characteristics in determining kinetics and corrosion control: Through testing of electrode potential and polarization resistance measurements, samples with larger thicknesses were less likely to corrode due to the formation of a more efficient physical barrier.

One of the alternatives used to protect the steel and prevent its deterioration is the corrosion inhibitors, which delay the depassivation time, by reinforcing the passive protective film or reducing the corrosion rate after depassivation (Myrdal, 2010; Lourenço & Souza, 2014). Migratory corrosion inhibitors are part of a new generation of organic inhibitor technology because they act by migrating through the pores of the structure, following the same path as water, and then acting on the metal surface, recreating the passive protection film (Chaussadent *et al.*, 2006; Bolzoni *et al.*, 2014). Many research on the MCI have been conducted, analyzing the performance and mechanism of action of these inhibitors when added to fresh concrete or when applied to the surface of hardened concrete, especially under chloride action (Vedalakshmi *et al.*, 2009; Zhi-Yong *et al.*, 2012, Zhiyoung *et al.*, 2016, Yu *et al.*, 2016).

According to Bavarian *et al.* (2018), the incorporation of amine carboxylate-based migratory corrosion inhibitors in reinforced concrete may prolong the service life of the structures. In their study, the authors monitored the efficiency of inhibitors using the

G109 (ASTM, 2013) standard, performing polarization resistance and electrode potential tests. Experimental results showed that the MCI-protected steel when compared to concrete without its addition, created an inhibitor system in aggressive environments such as seawater. Studies by authors Gartner *et al.* (2016), Kaurt *et al.* (2016), and Cai *et al.* (2015) also confirmed through corrosion testing that amine-based migratory inhibitors contribute to the protection of steel in the presence of chloride ions by delaying the initiation of the corrosion process. In this context, this research was conducted through the study of three factors that influence the development of steel reinforcement corrosion, by simulating an aggressive environment: concrete cover thickness, type of cement used, and addition of migratory corrosion inhibitor. For this evaluation, electrochemical and non-electrochemical techniques were used, such as electrode potential measurements and microscope visual analyzes.

## MATERIALS AND METHODS

### Characterization of materials

Concrete mixtures were prepared using two types of Portland cement: CP II F 32, commonly used and with no mineral additions, and CP IV 32 RS, containing mineral additions and sulfate resistant, therefore recommended for aggressive environments. **Tables 1** and **2** show the physical and chemical specifications of the CP II F 32 and CP IV 32 RS types of cement, respectively, provided by the manufacturer of these products.

The coarse aggregate used was gravel with a maximum diameter of 12.5 mm and fineness modulus of 6.27, according to the NBR NM 248 (ABNT, 2003) standard, and specific gravity of 2.87 kg/dm<sup>3</sup>, according to the NBR NM 52 (ABNT, 2009) standard. The fine aggregate (natural quartz sand) had a fineness modulus of 2.05, according to the NBR NM 52 (ABNT, 2009) standard, and a specific mass of 2.6 kg/dm<sup>3</sup>, according to the NBR NM 52 (ABNT, 2009) standard. The surface moisture content of the sand, measured on the day of concrete preparation, was 4.5%, NBR 9775 (ABNT, 2011). The steel bars used in the experiment were of type CA-50, with a nominal diameter of 10mm, ribbed. The adopted length was 30 cm, as indicated by the G109 (ASTM, 2013) standard. The surface preparation of the steel specimen was performed by cleaning to remove the oxides originally present in the bars, according to the procedure defined by the G1-03 (ASTM, 2017) standard.

The migratory corrosion inhibitor used in this research, designated as type x MCI, is based on an organic amine carboxylate technology. Manufacturer's data characterize the inhibitor as a dark brown liquid with the following specifications: pH: 9.5–12 (pure),

nonvolatile content: 44 - 55%, and density: 1.14 - 1.23 kg/L.

The formwork for casting the reinforced concrete specimens was made with prismatic geometry and dimensions of 15 x 11.5 x 28 cm, according to the recommendations of the G109 (ASTM, 2013) standard. 10 mm plywood sheets and fixing nails were used. In the positions where the steel should be placed, holes of the same diameter as the bars were drilled in both vertical surfaces of the formwork to prevent movement of the reinforcement during casting (**Fig. 1a**).

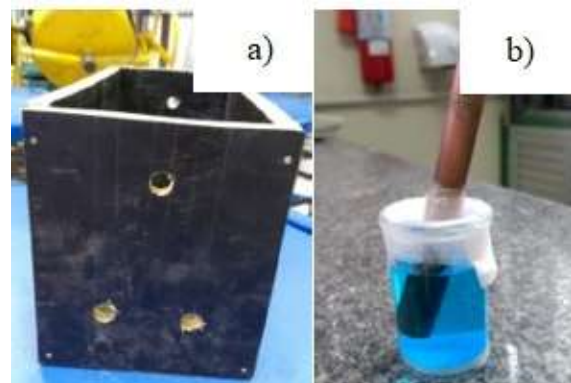
For the electrode potential measurements, a copper/copper sulfate reference electrode (**Fig. 1b**), made in the laboratory, was used, as described in the C876 (ASTM, 2015) standard.

**Table 1.** Physical characteristics of Portland types of cement.

Property	CP II F	CP IV 32
	32 cement	RS cement
Specific gravity (g/cm <sup>3</sup> )	3.06	2.83
Pozzolanic material content (%)	0	15-20
Initial setting time (min)	238	255
Final setting time (min)	284	305
Fineness in the sieve # 200 (%)	1.65	0.37
Blaine surface (cm <sup>2</sup> /g)	3.27	4.21
Compressive strength 3 days (MPa)	30.40	26.70
Compressive strength 7 days (MPa)	36.60	34.00
Compressive strength 28 days (MPa)	43.30	46.30

**Table 2.** Chemical characteristics of Portland types of cement.

Element (%)	CP II F 32 cement	CP IV 32
		RS cement
Loss on ignition 1000°C	5.42	3.74
SiO <sub>2</sub>	18.31	29.26
Al <sub>2</sub> O <sub>3</sub>	4.26	9.75
Fe <sub>2</sub> O <sub>3</sub>	2.87	4.12
MgO	3.39	2.50
CaO	61.22	45.01
SO <sub>3</sub>	2.67	2.18
Insoluble residue	1.14	25.44
Alkali equivalent	0.67	1.16



**Fig. 1** Formwork for casting the reinforced concrete specimens (a); copper/copper sulfate reference electrode (b).

### Concrete cover thickness

The concrete cover thickness of the upper reinforcement was varied in two levels, according to the standards used as the reference for this research. The class III environmental aggressiveness, adopted in this work and described by the NBR 6118 (ABNT, 2014) standard, recommends a covering of at least 4 cm. However, the G 109 (ASTM, 2013) standard for corrosion testing indicates a lower cover thickness (2.5 cm) to facilitate corrosion observation. The experiments were performed considering these two cover thicknesses, thus verifying their influence on the development of reinforcement corrosion.

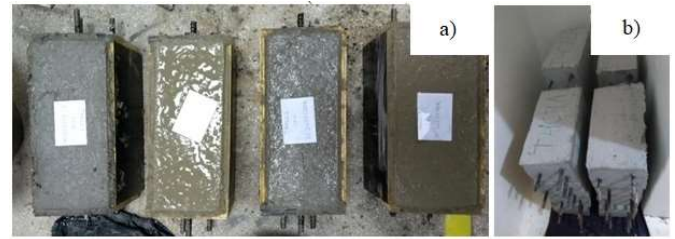
### Concrete mix design, casting, and curing

The characteristic compressive strength considered in the mix design was 30 MPa, adopted considering a class III environmental aggressiveness (marine environment) (ABNT, 2014). The slump was in the order of 100 mm with a variation of  $\pm 2$  mm, established according to the concrete application. In this case, they were considered structural elements with conventional casting (ABNT, 2016). The concretes were made in the proportion (by mass) of 1: 1.124: 1.852: 0.404 (cement: sand: gravel: water). **Table 3** shows the amount of input to produce 1 m<sup>3</sup> of the studied mixtures. The mixes variation was due to the different specific masses of the CP IV 32 RS (2.83 kg/dm<sup>3</sup>), and CP II F 32 (3.06 kg/dm<sup>3</sup>) types of cement. The variation between the mixes was due to the different specific gravities of the CP IV 32 RS (2.83 kg/dm<sup>3</sup>) and CP II F 32 (3.06 kg/dm<sup>3</sup>) types of cement. The water/cement ratio (w/c) of 0.404 was determined as a function of the cement class. The migratory corrosion inhibitor concentration in concretes with both types of cement was 0.6% of the total volume of the mixture, as indicated by the manufacturer.

The concretes were prepared according to indications of the NBR 5738 (ABNT, 2016) standard: first, the gravel and 80% of the water were mixed for 2 minutes. Soon after, sand, cement, and the rest of the water were added with the corrosion inhibitor. The inputs were then mixed for 3 min. Four different mixtures were produced: (a) concrete with CP IV 32 RS cement (4 cm cover), (b) concrete with CP IV 32 RS cement and addition of 0.6% of MCI (2.5cm cover), (c) concrete with CP II F 32 cement (4 cm cover), and (d) concrete with CP II F 32 cement and addition of 0.6% of MCI (2.5 cm cover).

**Table 3.** Consumption of materials for concrete production (per m<sup>3</sup>).

Material	CP IV concrete	CP II concrete
Cement (kg)	544.00	553.33
Sand (kg)	611.46	621.95
Gravel (kg)	1007.49	1024.77
Water (kg)	219.78	223.55
Corrosion inhibitor (L)	6	6



**Fig. 2** Casting of prismatic specimens of concrete (a); storage in a moist chamber (b).

Four specimens of prismatic reinforced concrete were cast for each mixture (**Fig. 2a**) to perform chloride penetration cycles and electrode potential measurements. These specimens were stored in a moist chamber with 100% relative humidity (**Fig. 2b**) for a period of 28 days. Then, they spent 3 weeks in the laboratory at room temperature for drying and finishing the curing process.

### Compressive strength tests

The compressive strength tests were performed according to the NBR 5739 (ABNT, 2018) standard. Four cylindrical specimens of 10 cm diameter and 20 cm height were molded for each mixture, totaling sixteen specimens. After demolding the specimens, they were submerged in a water tank saturated with calcium hydroxide at 23°C for 28 days (curing time). For the compressive strength test, the automated 200 t. EMIC universal testing machine with a load application rate of approximately 1 MPa/s was used.

### Aggressive environment simulation

To simulate an aggressive class III environment, according to the classification of the NBR 6118 (ABNT, 2014) standard, the reinforced concrete specimens were submitted to chemical attack acceleration cycles. The substance used in these attacks was sodium chloride (NaCl) at a concentration of 6% and the period of execution of the wetting and drying cycles were 4 and 3 days, respectively. It is worth noting that the time interval between measurements was reduced when compared to that indicated by the G 109 (ASTM, 2013) standard, which recommends monthly measurements. During the wetting period, the solution was added to a recipient of acrylic material, containing only the sidewalls, which were fixed and centered on the upper base of the specimen, as described by the G109 (ASTM, 2013) standard (**Fig. 3**). Then the liquid was removed and the drying period began. The complete cycle was performed for one week and repeated 16 times.

### Electrode potential measurement technique

The electrode potential measurement technique was used to verify the progression of corrosive activity in each sample. This way, it was possible to evaluate the



Fig. 3 Chloride ion induction acceleration method in concrete.

The protection provided by the migratory corrosion inhibitor and the concrete covering, as well as the influence of the cement type on the steel reinforcement corrosion. This test, standardized by the C876 (ASTM, 2015) standard, measures the potential difference (mV) between the working electrode (steel) and a reference electrode (in this case, the copper/copper sulfate) as an indication of electrochemical corrosion activity in the sample. Table 4 presents the evaluation criteria of the corrosion phenomenon, through a correlation between potential intervals and the probability of its occurrence (Freire, 2005).

The equipment used to measure this corrosion potential was a high impedance (> 10MΩ, 200mV scale) voltmeter, as prescribed by the C876 (ASTM, 2015) standard. Measurements were made by forming an electrical cell, where the positive terminal of the voltmeter was connected to the upper steel bar (working electrode), and the negative terminal was connected to the copper/copper sulfate reference electrode (Fig. 4).

**Visual analysis**

With the end of the chemical attack cycles and potential measurements, the prismatic specimens were ruptured in the hydraulic press, and the steel bars were removed for visual analysis and determination of the gravimetric corrosion rate.

With the end of the chemical attack cycles and potential measurements, the prismatic specimens were ruptured in the hydraulic press, and the steel bars were removed for visual analysis and determination of the gravimetric corrosion rate. Firstly, the steel bars were cleaned according to G1-03 (ASTM, 2011) standard: they were immersed in 1:1 hydrochloric acid solution with 3.5 g/L hexamethylenetetramine for ten minutes.

Table 4. Corrosion potential evaluation criteria according to the C876 standard.

Corrosion potentials – E <sub>corr</sub> (mV)	Corrosion probability (%)
E <sub>corr</sub> > -200 mV	< 10 %
-200 mV > E <sub>corr</sub> > -350 mV	uncertain
E <sub>corr</sub> < -350 mV	> 90 %

These bars were then washed with plenty of water and brushed with hard plastic bristles to remove all corrosion products. It took four 10-minute baths for each interleaving cleaning, and after that, the bars were immersed in acetone for two minutes. Afterward, they were weighed to determine the weight loss during the corrosion tests period. According to Ribeiro (2010), the gravimetric corrosion rate (CR) can be determined by Eq. (1):

$$CR = \frac{KW}{ATD} \tag{1}$$

where:

K = constant (for CR in μm/year, K = 8.76 x 10<sup>7</sup>);

W = weight loss (g);

A = exposure area (cm<sup>2</sup>);

T = exposure time (h);

D = density (for CA-50 steel, D = 7.85 g / cm<sup>3</sup>).

In the present study, the exposure area was 20 cm<sup>2</sup> and the exposure time was 2352 hours (98 days). After cleaning and weighing, the steel bars were analyzed under the Leica 95 optical microscope, to observe in detail the general aspects inherent to corrosion products, with a 6.3-fold increase.



Fig. 4 Electrode potential measurement system using a voltmeter.

Table 5. Average compressive strength values of concrete at 28 days.

Concrete (by cement type and MCI addition)	Average compressive strength at 28 days (MPa)	Standard deviation (MPa)
CP IV 32 RS without MCI	37.1	2.1
CP II F 32 without MCI	46.6	3.1
CP IV 32 RS with MCI	43.2	3.3
CP II F RS with MCI	43.1	5.0

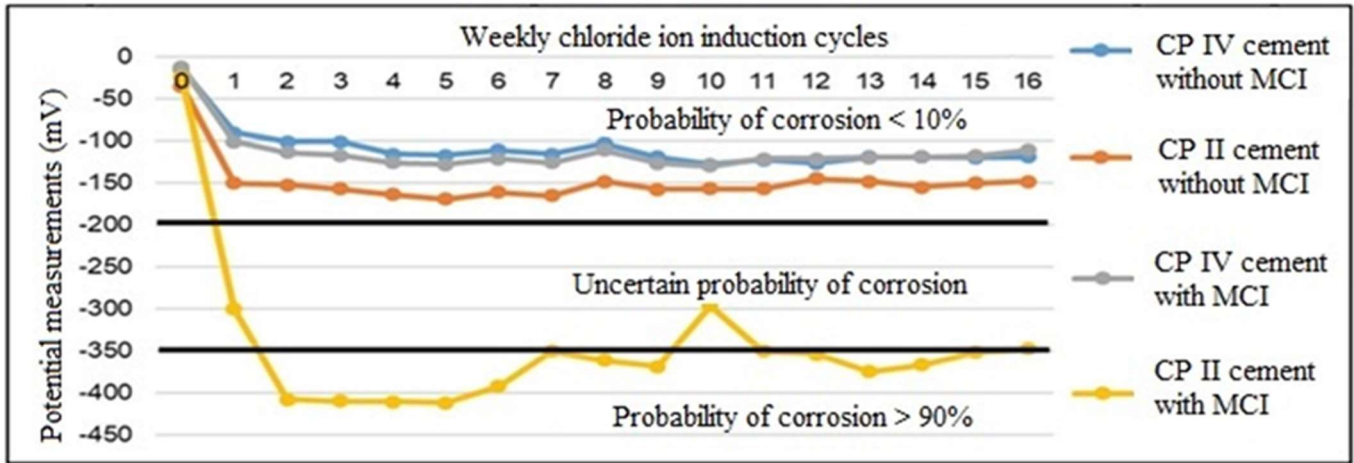


Fig. 5 Corrosion potential measurements on concretes over time.

**RESULTS AND DISCUSSIONS**

**Concrete compressive strength**

The average compressive strength at 28 days adopted for the mixtures was 36.6 MPa, equivalent to the characteristic design strength of 30 MPa. The mean compressive strength and standard deviation values of the test results are shown in Table 5. Both results were satisfactory. The standard deviation was considered small and regular for all concretes.

**Electrode potential measurements**

The corrosion potential was analyzed according to the type of cement (CP IV 32 RS and CP II F 32), the presence of corrosion inhibitor, and the thickness of the reinforcement concrete cover (2,5 and 4 cm) of the specimens. Fig. 5 illustrates the electrode potential (mV) readings as a function of the weekly chloride ion induction cycles for the concretes. Specimens without MCI were tested with a 4 cm cover, while those with inhibitors were tested with a 2.5 cm cover.

Fig. 5 shows that in the first readings taken before the samples were submitted to the wetting and drying cycles in NaCl solution (cycle 0), the formation of the passive protective film was verified since the potential values obtained were higher than -200 mV. This proves that the reinforcement was protected by the alkaline medium present in the concrete.

Using the data from Fig. 5, one of the cycles was chosen to perform a spot analysis of the results. Therefore, Fig. 6 shows the potential measurements at the end of week 14 of chloride ion induction cycles for reference concretes (without MCI) with CP IV 32 RS and CP II F 32 cement and 4 cm concrete covering (blue) and for concretes with the addition of migration corrosion inhibitor and 2.5 cm concrete covering (green).

Regarding the influence of the cement type, in the analysis of Figure 6, it was possible to verify that the concrete with CP II cement presented more negative

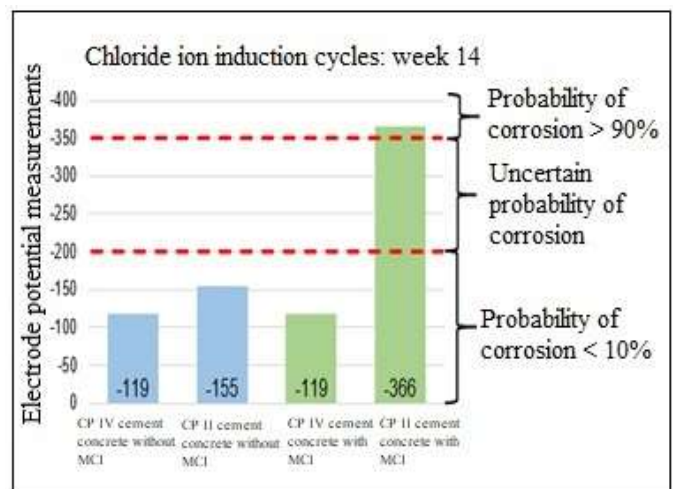


Fig. 6 Potential measurements on concretes without MCI (with 4 cm reinforcement cover) at week 14.

electrode potential measurements in the two levels of concrete covering, which indicates a higher susceptibility to the occurrence of corrosion. According to Rizzon and Andrade (2007), the presence of filler instead of clinker in CP II may be responsible for a higher chloride ions content in the mixture.

In their study, the authors verified the penetration of chloride ions in concrete containing cement with filler and another with cement with mineral additions in its composition: in the first one, they found a higher diffusion coefficient of these ions. Similarly, a possible positive influence of CP IV cement on the steel's protection against corrosion can be observed, due to its less negative readings, remaining within the smaller than 10% probability range of corrosion. This fact may be related to the addition of pozzolan in CP IV cement, increasing its resistance to aggressive environments, as mentioned by Battagin (2011) and Neville (2016).

Fig. 6 also allows to verification of the influence of the concrete cover thickness on the potential corrosion measurements. According to Neville (2016), the greater the cover thickness, the longer the time until the

chloride concentration near the steel reaches the limit value for the development of corrosion. In this research, the specimens were exposed to the same aggressive agent content, and, during the same period of time, the results obtained for the mixtures with CP II cement presented extreme values at both levels of covering. Even with the addition of MCI, in the specimens with the lowest concrete covering, there was an increase in the degree of corrosion presented. Rocha *et al.* (2014) also verified this positive influence of the increase of the cover thickness in the potential readings in chloride-containing concretes, finding a reduction in the degree of corrosion.

Still, in **Fig. 6**, the values obtained for the CP II cement concrete, with smaller and larger covering thicknesses, were -366 mV and -155 mV, respectively. According to the C876 (ASTM, 2015) standard, the value of -366 mV characterizes a probability greater than 90% for corrosion development, while -115 mV indicates a probability of less than 10%. Therefore, in the first case, there is a probable depassivation of the reinforcement and the beginning of the corrosive process since, according to Vagheti (2005), this transition in the potential measurements indicates that the reinforcement goes from a passive state to an active corrosion state. The performance of the migratory corrosion inhibitor was another factor considered in the interpretation of these results. Specimens containing CP II cement with MCI obtained potential measurements of less than -350 mV

**Table 6.** Weight loss results and gravimetric corrosion rate of steel specimens.

Specimen	Cover thickness (cm)	Initial mass of steel (g)	Final mass of steel (g)	W (g)	CR ( $\mu\text{m}/\text{year}$ )
CP IV 32 RS without MCI	4	37.1	2.1	0	0
CP II F 32 without MCI	2.5	46.6	3.1	0	0
CP IV 32 RS with MCI	4	43.2	3.3	0	0
CP II F RS with MCI	2.5	43.1	5.0	0.2	38.75



**Fig. 7** Indication of signs of corrosion on steel specimens.

In almost all cycles (Figure 6), which according to the C876 (ASTM, 2015) standard, is considered a high probability for the development of corrosion. However, in the last cycles, it was possible to notice a trend of increasing values, changing to the uncertainty range of the corrosion probability. Therefore, to affirm the effective performance of the MCI, it would be necessary to extend the duration of the tests to verify the tendency to increase these values. The CP IV cement concretes, with and without the addition of MCI, presented a linearity in the results obtained in both cases. Despite the different cover thicknesses, both remained in the low probability of corrosion range and a possible inhibitor action could be observed.

The same tests were performed by Bavarian *et al.* (2007) and Bavarian *et al.* (2018). According to the authors, MCI acts on steel through a coordinated bond between amine nitrogen and metal, and nitrogen is adsorbed to steel. This adsorption of cations increases the ionization potential of metals and slows down the corrosion process. The positive performance of the migratory corrosion inhibitor in the protection of steel was also verified in other studies, in which the concretes with the addition of MCI, in the presence of chloride ions, presented a delay in the initiation of the corrosion process when compared to those without inhibitor. (Vedalakshmi *et al.*, 2009; Gartner *et al.*, 2016; Kaur *et al.*, 2016; Cai *et al.*, 2015).

### Gravimetric corrosion rate and visual analysis

For a qualitative analysis of steel bar mass loss, a visual inspection was first performed. **Fig. 7** shows the steel specimens immediately after their removal from the CP IV cement concrete specimens, with 4 cm and 2.5 cm coverings, and from the CP II cement concrete specimens, with 4 cm and 2.5 cm coverings, respectively.

**Table 6** shows the results of weight loss and gravimetric corrosion rate (CR) of the bars located on the upper part of the prismatic specimens (**Fig. 3**), in which the electrode potential difference measurements and the cycle of accelerated attack of chloride ions were performed.

It was not possible to effectively quantify the weight loss of the steel bars from CP I V cement concrete and from the CP II cement with the larger concrete cover due to their low mass variations. For this analysis to be feasible, it would be necessary to extend the period of chemical attack and wait for the corrosive process to advance, thus obtaining greater corrosion products. Only the steel bar of concrete with CP II cement and 2.5 cm covering showed a consistent result: despite a small weight loss, it was possible to calculate the gravimetric corrosion rate, which was 38.75  $\mu\text{m}/\text{year}$ . These data confirm the results found in the electrode potential readings, indicating the occurrence of the corrosive process in this sample.

Then, the steel bars were taken for viewing under an optical microscope and, as verified, it was possible to identify corrosion points in the concrete sample with CP II cement and 2.5 cm covering. **Fig. 8** shows the deterioration of the metal surface through the presence of corrosion products, such as detrition and different shades. Results such as these were also found by Bolina (2008), in which the visual aspects of the steel bars analyzed were consistent with the corrosion rates.

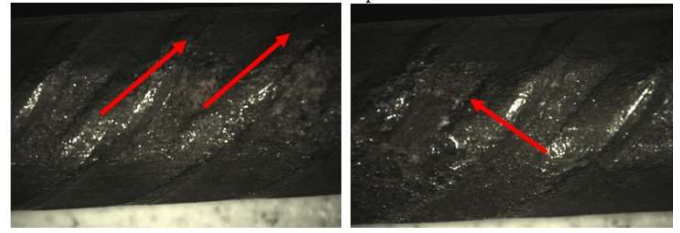
## CONCLUSION

Through this study, it was found that the addition of migratory corrosion inhibitor, cover thickness, and type of cement influenced the development of steel corrosion.

It was concluded that the cement CP IV 32 RS acted in the protection of the steel against corrosion since all the samples in which it was used presented more positive potential measurements. In addition, regardless of the concrete cover thickness for the reinforcement, constant values were obtained in the 14th weekly cycle of -119 mV with and without inhibitor, respectively, in the samples with such cement. These values remained within the 10% probability of corrosion, indicating that this cement delays the initiation of steel corrosion, providing greater protection against penetration of aggressive agents. The results involving CP II F 32 cement showed that it did not promote equal protection to steel, not impeding the development of the corrosive process. The specimens with this material presented more negative values of potential measurements at both covering levels, indicating a greater susceptibility to reinforcement corrosion in aggressive environments.

In CP II cement concrete there was a greater influence on the cover thickness than in the CP IV cement mixtures. For the sample with cement CP II and greater covering, the potential measurement in the 14<sup>th</sup> cycle was -155 mV, remaining within the 10% probability of corrosion. The sample with a smaller concrete covering achieved lower values during the entire measurement period, reaching -366 mV in the 14th cycle, being within the 90% probability of corrosion and uncertain corrosion during the measurement period. Therefore, reinforcement concrete covering using CP II cement effectively influenced the development of steel corrosion.

With the reduction of the CP IV cement concrete cover thickness, one could identify a possible action of the corrosion inhibitor, since the potential values remained constant at both levels analyzed. In the case of CP II cement, despite the more negative values, there



**Fig. 8** Steel bar aspects of CP II cement and 2.5 cm concrete cover specimen after chloride-induced corrosion.

Was a tendency to increase the potential as a function of time. With the prolongation of the testing period, this fact could possibly also be attributed to the addition of the migratory corrosion inhibitor. The results of the gravimetric corrosion rate were relevant only for concrete with CP II cement and a 2.5 cm cover, confirming the potential corrosion measurements. The visual aspects observed were coherent and basic corrosion characteristics can be identified.

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