Revista ALCONPAT
www.revistaalconpat.org
eISSN 2007-6835
Revista de la Asociación Latinoamericana de Control de Calidad, Patología y Recuperación de la Construcción

Influence of temperature on the electrical resistivity of concrete and kinect corrosion of reinforcement

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DOI: https://doi.org/10.21041/ra.v14i1.709

Received: 07/11/2023 | Received in revised form: 28/11/2023 | Accepted: 07/12/2023 | Published: 01/01/2023

ABSTRACT

The work evaluated the influence of temperature on the concrete electrical resistivity measurements and corrosion kinetics in reinforced concrete structures subjected to chlorides. The concretes were mechanically characterized at 28 and 90 days. After 204 days, the specimens were subjected to temperature cycles ranging from 55 °C to -5 °C. The results indicated that the corrosion kinetics and electrical resistivity varied with the temperature changes. At higher temperatures, dosages contaminated with Cl^- showed a high probability of corrosion and a decrease in electrical resistivity values, however, at negative temperature, the probability of corrosion was insignificant and the electrical resistivity values were the highest.
Keywords: reinforcement concrete; durability; corrosion; electrical resistivity; temperature.

Cite as: Chiaradia, L. C., Almeida, F. C. R., Aguilar, M. T. P., Figueiredo, E. J. P. (2024), "*Influence of temperature on the electrical resistivity of concrete and kinect corrosion of reinforcement*", Revista ALCONPAT, 14 (1), pp. 1 – 12, DOI: https://doi.org/10.21041/ra.v14i1.709

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Contribution of each author
In this work, Figueiredo, E. J. P contributed with the original idea and guidance of the work and corrections, Aguilar, M. T. P. and Almeida, F. C. R contributed with the co-guidance of the work, assisting in the development, data processing and writing, Chiaradia, L. C. contributed to the development of the methodology, experimentation, data collection, data processing, writing the work and final presentation of the results.

Discussions and subsequent corrections to the publication
Any dispute, including the replies of the authors, will be published in the third issue of 2024 provided that the information is received before the closing of the second issue of 202.

Influencia de la variación de temperatura en la resistividad eléctrica del hormigón y en la cinética de corrosión de la armadura en hormigón armado

RESUMEN

El trabajo evaluó la influencia de la variación de temperatura em las medidas de resistividad eléctrica y cinética de corrosión em estructuras de hormigón armado sometidas a cloruros. Los hormigones se caracterizaron física y mecánicamente a los 28 y 90 días. Después de 204 días, las muestras se sometieron a ciclos de temperatura de ida y vuelta de 55°C hasta -5°C. Los resultados indicaron que la cinética de corrosión y la resistividad eléctrica variaron com los cambios de temperatura. A temperaturas más altas, las trazas contaminadas con Cl^- mostraron uma alta probabilidad de corrosión y una disminución em los valores de resistividad eléctrica, sin embargo, a temperatura negativa la probabilidad de corrosión fue insignificante y los valores de resistividad eléctrica fueron los más altos.

Palavras-chave: hormigón armado; durabilidade; corrosión; resistividad eléctrica; temperatura.

Influência da temperatura na resistividade elétrica do concreto e na cinética de corrosão da armadura

RESUMO

O trabalho avaliou a influência da variação de temperatura nas medidas de resistividade elétrica e na cinética de corrosão em estruturas de concreto armado sujeitos a cloretos. Os concretos foram caracterizados fisicamente e mecanicamente aos 28 e 90 dias. Após 204 dias, as amostras foram submetidas a ciclos de ida e volta de temperatura partindo dos 55°C até -5°C. Os resultados indicaram que a cinética de corrosão e a resistividade elétrica variaram com a alteração da temperatura. Em temperaturas mais elevadas, os traços contaminados com Cl- demonstraram uma alta probabilidade de corrosão e uma diminuição dos valores de resistividade elétrica. Porém, na temperatura negativa a probabilidade de corrosão foi insignificante e os valores de resistividade elétrica os mais elevados.

Palavras-chave: a concreto armado; durabilidade; corrosão; resistividade elétrica; temperatura.

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1. INTRODUCTION

Reinforced concrete structures are exposed to various environmental conditions, such as humidity variations, temperature variations, and contact with aggressive elements (Andrade *et al*., 1988; Yousuf *et al*., 2017). Such factors can cause reinforcement corrosion, one of the main problems of reinforced concrete constructions. It harms the durability of structures and can lead to expensive repairs. In some cases, it may be necessary to wholly or partially replace the reinforcement and/or structural reinforcements to extend the durability and prolong the useful life of the reinforced concrete (Helene, 1993; Laurentino *et al*., 2021). It occurs because the products arising from corrosion are expansive, generate cracks in the concrete, reduce the adhesion between the reinforcement and the concrete, in addition to causing a loss of section in the reinforcement, damaging the structure's bearing capacity (GjØrv, 2015; Chauhan and Sharma, 2019).
When evaluating durability, the corrosion of reinforcement, the characterization of the concrete, and the environment where it will be exposed must be considered. The correct choice of materials and compatible definition of the construction methods to be used, as well as maintenance throughout its use, also influences the structure's performance throughout its useful life (Figueiredo and Meira, 2013).
Chloride ions play an essential role in the depassivation process of the steel armor's protective film. Corrosion induced by chlorides is one of the most common and worrying causes of degradation of reinforced concrete structures, as they are of the pitting type, formed in localized and deep areas (Torres, 2011). At these points where chlorides, together with water and oxygen, come into contact with the steel, anodic zones are formed, and the movement of ions occurs, causing the reduction of the bar and, consequently, the reduction of its section and loss of its resistance (Figueiredo, 2005).
Different tests analyze the corrosion of the reinforcement and the conditions of ion mobility within the concrete. Non-destructive tests to determine electrical resistivity and evaluate corrosion are widely used for inspecting and monitoring structures, as they are quick and easy to perform. With these techniques, it is possible to obtain information regarding the internal conditions of the concrete and the corrosive process of the reinforcement (Wosniack *et al*., 2021).
However, the results obtained through monitoring tests may change due to variations in concrete temperature. This parameter directly influences ionic mobility and, consequently, corrosion kinetics. Understanding how the structure behaves against the action of aggressive agents at different temperatures contributes to the understanding and interpretation of the results of tests carried out in different climatic conditions (Chauham and Sharma, 2019). Raphael and Shalon (1971) demonstrated that the corrosive process doubles for every 20 °C increase in temperature. Tuutti (1982) investigated the effects of low temperatures on concrete structures and concluded that the rate of corrosion of steel is reduced ten times for each decrease of around 20 °C (at temperatures below 0 °C); Alhozaimy *et al*. (2014) concluded that the increase in temperature led to changes in the armor's passivating film, destabilizing the oxide phases in such a way as to enhance the corrosive process.
Noort (2016), Mendes (2018), and Medeiros and Júnior (2019) concluded that the w/c ratio inversely proportionally influences the electrical resistivity values in concrete, with the lower the w/c ratio, the higher the concrete resistivity.
In this context, this research analyzes the effect of the water/cement ratio and temperature variation on the electrical resistivity and corrosion kinetics of reinforcement in concrete contaminated and not contaminated with chlorides.

2. MATERIALS AND EXPERIMENTAL PROGRAM

2.1 Materials

High initial strength Portland cement (CP V ARI) was used due to the low level of additions (90-100% clinker + calcium sulfate, by mass).

Quartz sand and gneiss crushed stone were used as fine and coarse aggregates, in this order, as per the characterization presented in Table 1.

Table 1. Physical characterization of aggregates

Property	Quartz sand	Gneiss crushed stone
Unit mass	1.301 kg/dm^3	1.388 kg/dm^3
Specific mass	2.604 kg/dm^3	2.646 kg/dm^3
Absorption	0.60 %	0.50 %
Fineness modulus	2.068	5.603
Maximum diameter	1.2 mm	12.55 mm
Void coefficient	50.04 %	47.52 %

CA50 steel bars, 10 mm in nominal diameter, were used as reinforcement. The diameter was chosen due to its wide commercial use in construction. Before use, the bars were cut to the pre-stipulated size and subjected to the cleaning process by standard G-1/03 (ASTM, 2017).

Four basic characteristics differed in the w/c ratio and chloride contamination. In contaminated concrete, 1.65% of sodium chloride was added to the mixing water about the cement mass to reach 1% of chlorides in the concrete composition due to the atomic composition of chlorine in the NaCl compound.

The traits are presented in Table 2. To achieve workability in concretes with a w/c ratio of 0.45, a second-generation superplasticizing additive (Sika® Viscocrete®) was used, with pH = 4.5 ± 1.0 and free of chloride ions.

Table 2. Dosages of concrete (by mass)

Identification	Cement	Sand	Gravel	Water	Additive	NaCl
0,60 ref.	1	2	2.5	0.60	-	-
0,60 Cl^-	1	2	2.5	0.60	-	0.0165
0,45 ref.	1	2	2.5	0.45	0.003	-
0,45 Cl^-	1	2	2.5	0.45	0.003	0.0165

All mixtures manufactured reached 105±5mm in the cone slump test tests, thus presenting similar consistency and workability.

Cylindrical specimens of 10 cm in diameter and 20 cm in length were molded for the characterization of concrete analysis of electrical resistivity when subjected to temperature cycles, and prismatic specimens of 20 cm in length, 20 cm in width, and 7 cm in height, with a 30 mm covering layer on two sides of the test piece, for exposure to temperature cycles to evaluate corrosion potential and corrosion speed.

The cylindrical bodies were demolded after 24 hours of molding, and the prismatic bodies after 48 hours, as indicated by the NBR 5738 standard (ABNT, 2015). After demolding, the specimens were identified and placed for curing in a humid chamber with a temperature of 24 °C ±5 °C and humidity of 95% ±5%. The bodies remained in these conditions until the physical and mechanical characterization stages that took place at 28 and 90 days of age and until exposure to temperature cycles took place from 204 days.

2.2 Experimental program

The physical and mechanical characterization of concretes was carried out in cylindrical specimens using compression resistance tests (ABNT NBR 5739, 2018), modulus of elasticity by forced resonant frequency (ASTM C215, 2019), water absorption and void index (ABNT NBR 9778, 2009) at ages 28 and 90 days. At the same time, the specimens were kept in a humid chamber and monitored until they showed an active state of reinforcement corrosion in contaminated samples (204 days).

The samples were then subjected to exposure to temperature cycles to analyze surface electrical resistivity (AASHTO T358, 2015), corrosion potential (ASTM C876, 2015), and corrosion speed (by the linear polarization method with a scanning interval of ± 15mV about the open circuit potential). A Copper/Copper Sulfate reference electrode was used for the corrosion potential tests. For the linear polarization test, a saturated Calomel reference electrode and a sheet counter electrode—stainless steel in the dimensions of the largest face of the prismatic specimen- were used.

The temperature cycles were carried out by varying the temperature, where the specimens were subjected to a round-trip cycle starting from a temperature of 55 °C down to -5 °C in a climate chamber with temperature and humidity control. The stabilization temperatures for carrying out the tests were 55 °C, 40 °C, 22 °C, 10 °C, 5 °C and -5°C.

To measure the surface and internal temperature of the specimens, a surface infrared thermometer and thermocouples inserted inside the concrete during molding were used at the same depth as the steel bars. The exposure time of the samples to the temperatures was necessary to stabilize the temperature on the surface and inside the sample. A variation of ± 2 °C was allowed for each temperature range defined in the study. Humidity was set at 80%, so the concrete pores had high internal humidity but without saturation, allowing oxygen penetration.

All assays were performed in triplicate, and the results were statistically analyzed using the analysis of variance (ANOVA) method and the pairwise test (Tukey test) when necessary.

3. RESULTS AND DISCUSSIONS

3.1 Characterization of concrete

Table 3 presents the average results of the properties analyzed in the concrete characterization tests at the two ages analyzed.

Through statistical analysis, it was possible to verify that there was no significant evolution in water absorption values in the 0.60 mix contaminated at different ages. The values of contaminated and uncontaminated w/c 0.45 samples can be considered statistically equivalent compared to the same age.

The void index results for the two ages of the analyzed traits only showed a statistically relevant variation for the contaminated 0.45 w/c ratio trait.

In the compressive strength results, only the 0.45 contaminated mix did not show a statistically significant evolution when comparing the results at the two ages.

Table 3. Characterization of concretes in the hardened state

Dosage	0,60 ref.		0,60 Cl⁻		0,45 ref.		0,45 Cl⁻	
Age	**28d**	**90d**	**28d**	**90d**	**28d**	**90d**	**28d**	**90d**
Water absorption (%)	7.76	7.41	6.82	6.72	4.81	4.55	4.92	4.55
Void ratio (%)	16.47	15.98	14.59	14.36	10.69	10.15	10.92	10.14
Compressive strength (MPa)	33.00	39.00	35.00	40.00	57.00	66.00	49.00	54.00
Modulus of elasticity (GPa)	36.00	35.00	36.00	35.00	36.00	36.00	37.00	37.00

When comparing the results of the traits with a w/c ratio of 0.60, it was possible to verify through the Tukey test that there is no statistical difference between the results for the contaminated and uncontaminated traits at the same age.
The elasticity moduli did not vary between the traits and ages analyzed, which can be explained by the method adopted.

3.2 Temperature cycles

The temperature variation cycle began at 204 days of age when signs of corrosive activity were observed in the specimens contaminated with chlorides. Figure 1 shows the corrosion potential values of the specimens with and without chloride contamination, and the reinforcement corrosion ranges according to standard C876-15 (ASTM, 2015).

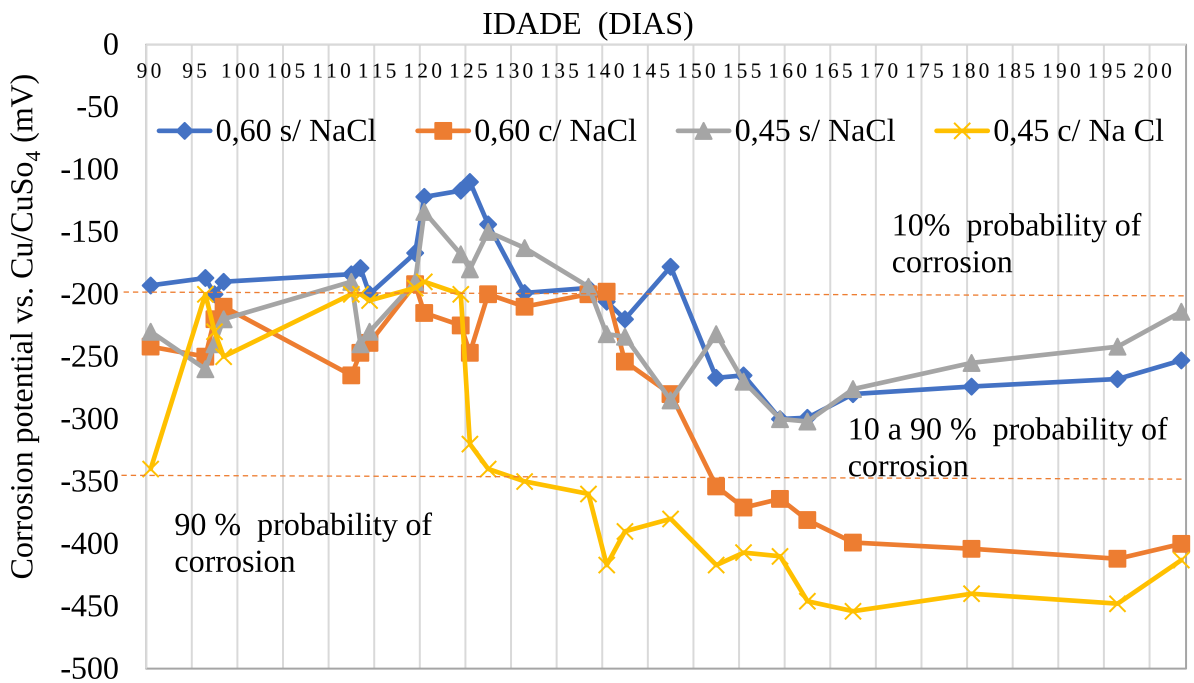

Figure 1. Corrosion potential during the monitoring phase

After confirming the beginning of the corrosive process in the reinforced specimens contaminated by chlorides, the stage of exposing the specimens began. Figure 2 shows the corrosion potential values measured for the mixes not contaminated with Cl⁻ as a function of the concrete temperature variation.

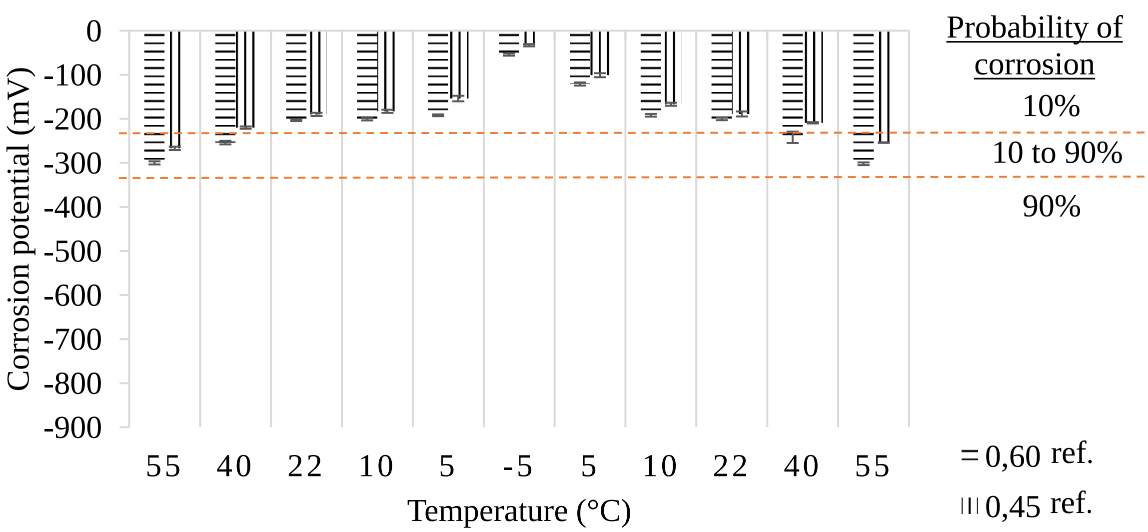

Figure 2. Corrosion potential (Cu/$CuSO_4$ electrode) at different temperatures in dosages not contaminated by chlorides (ref.).

For the two w/c ratios in the uncontaminated samples, it was possible to notice that with the increase in temperature, the corrosion potential values migrated from a 10% probability of corrosion to the uncertainty zone (10 to 90%), especially at the highest temperature. It can be seen that none of the uncontaminated mixes reached the zone of high probability of corrosion throughout the cycle. The dosage with a w/c ratio of 0.60 presented more electronegative values than the mix with a w/c ratio of 0.45.
Figure 3 shows the corrosion potential values of mixes contaminated with Cl^- as a function of the concrete temperature variation.

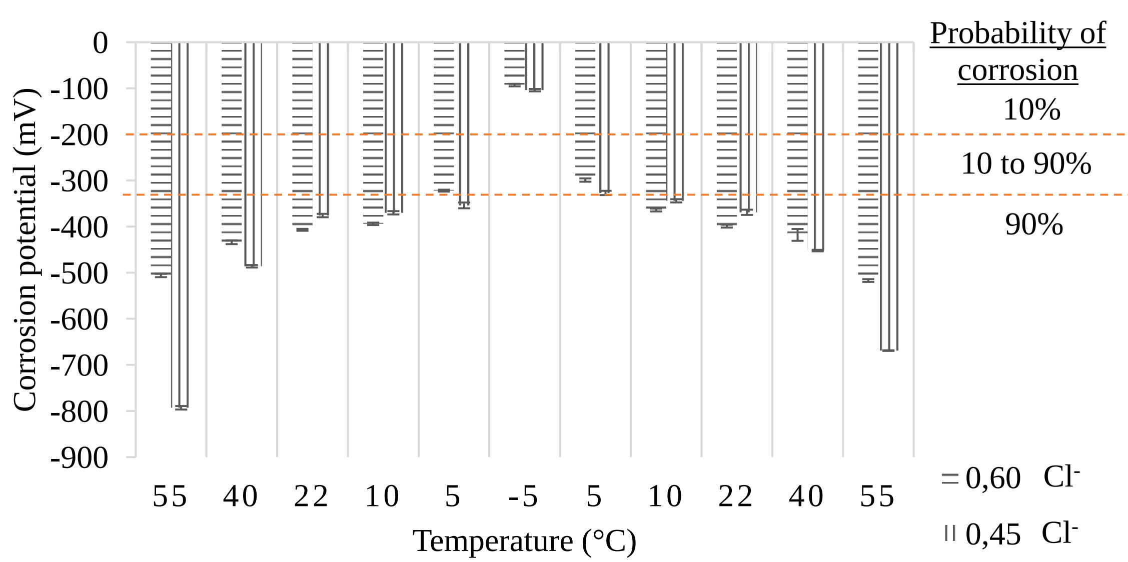

Figure 3. Corrosion potential (Cu/$CuSO_4$ electrode) at different temperatures in mixes contaminated by chlorides (Cl^-).

By analyzing the results, it can be inferred that readings carried out below a temperature of 10 °C generated values in the zone of uncertainty for the contaminated dosages. Moreover, the results indicated a 10% probability of corrosion at negative temperatures even with the reinforcement depassivated. On the other hand, at temperatures above 22 °C, there was a tendency to observe more electronegative results, especially at the highest temperature (55 °C). In the samples contaminated with chlorides, the tendency of the mix with the lowest w/c ratio to remain with less electronegative values was not observed; there was a variation between them throughout the cycle. The results of corrosion speed as a function of temperature variation for uncontaminated samples are presented in the Figures and the analysis ranges proposed by Andrade *et al*. (1997).

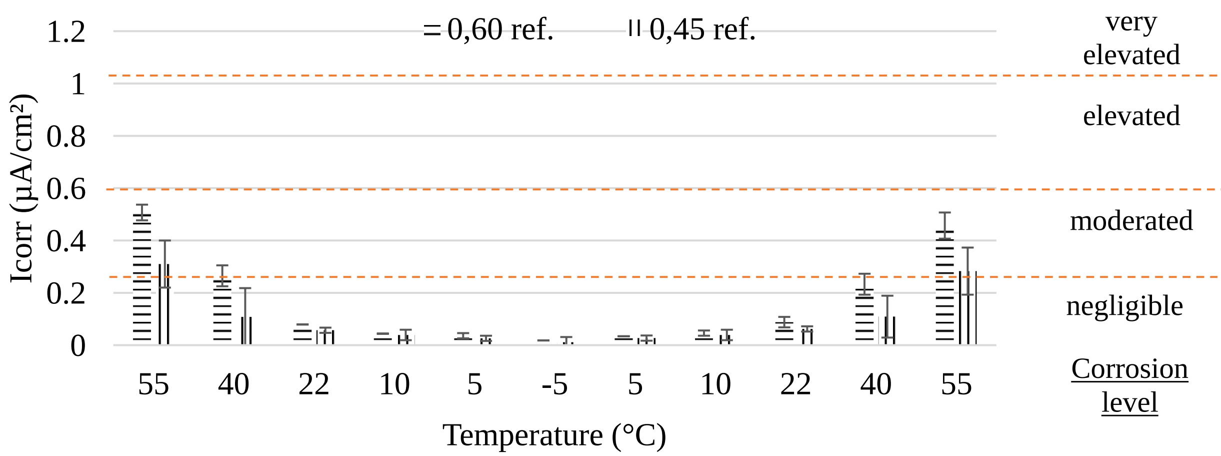

Figure 4. Corrosion speed at different temperatures in samples not contaminated by chlorides (ref.).

Uncontaminated concrete at temperatures of 22 °C and below showed negligible corrosion levels. At the highest temperature, the w/c ratio of 0.60 showed average values in the border region between moderate and high corrosion levels.
Figure 5 presents the results of corrosion speed as a function of temperature variation for samples contaminated with chlorides.

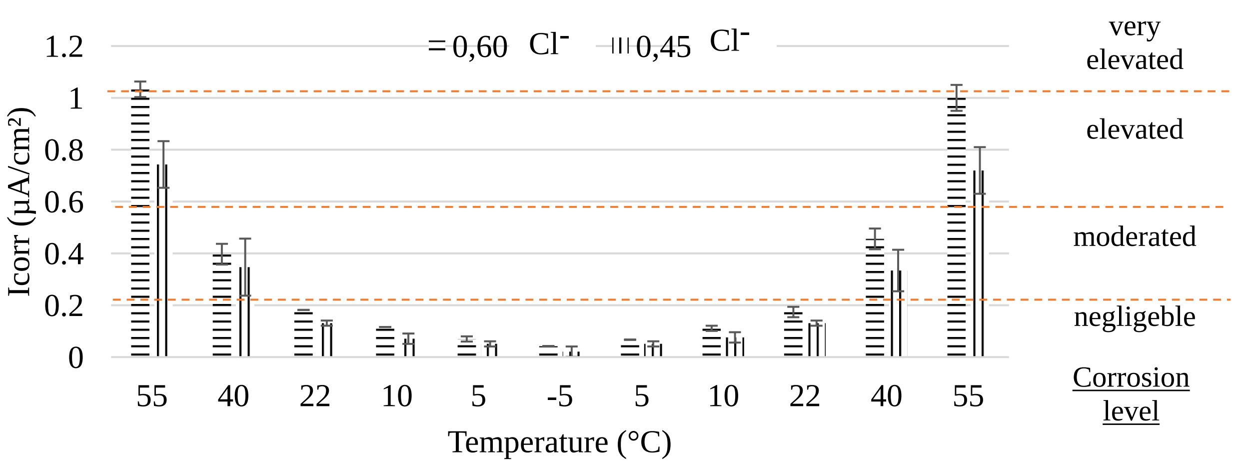

Figure 5. Corrosion speed at different temperatures in mixes contaminated by chlorides (Cl^-).

When exposed to the highest cycle temperature (55 °C), the contaminated 0.60 w/c ratio concrete reached a very high level of corrosion, while the contaminated 0.45 w/c ratio showed high corrosion. At temperatures below 10 °C, the contaminated concrete showed negligible levels of corrosion even though the reinforcement was depassivated.
It was noticed that the greatest variation in results occurred at higher temperatures for both contaminated and uncontaminated samples. According to Østvik (2004), this is due to the fact that

at higher temperatures, the probability of two molecules colliding is greater. This higher collision rate increases kinetic energy, affecting the activation energy of chemical reactions.
The temperature variation generated an influence directly proportional to the corrosion rate, and as the temperature increased, the corrosion rate also increased.
The dosages with a w/c ratio of 0.45 showed lower corrosion speed values throughout the entire exposure cycle than those with a w/c ratio 0.60.
The results of the surface electrical resistivity tests for the specimens subjected to the temperature cycle for the uncontaminated mixes are presented in Figure 6, as well as the corrosion risk indication ranges for concrete contaminated with chlorides, as suggested by Bungey and Millard (2001).

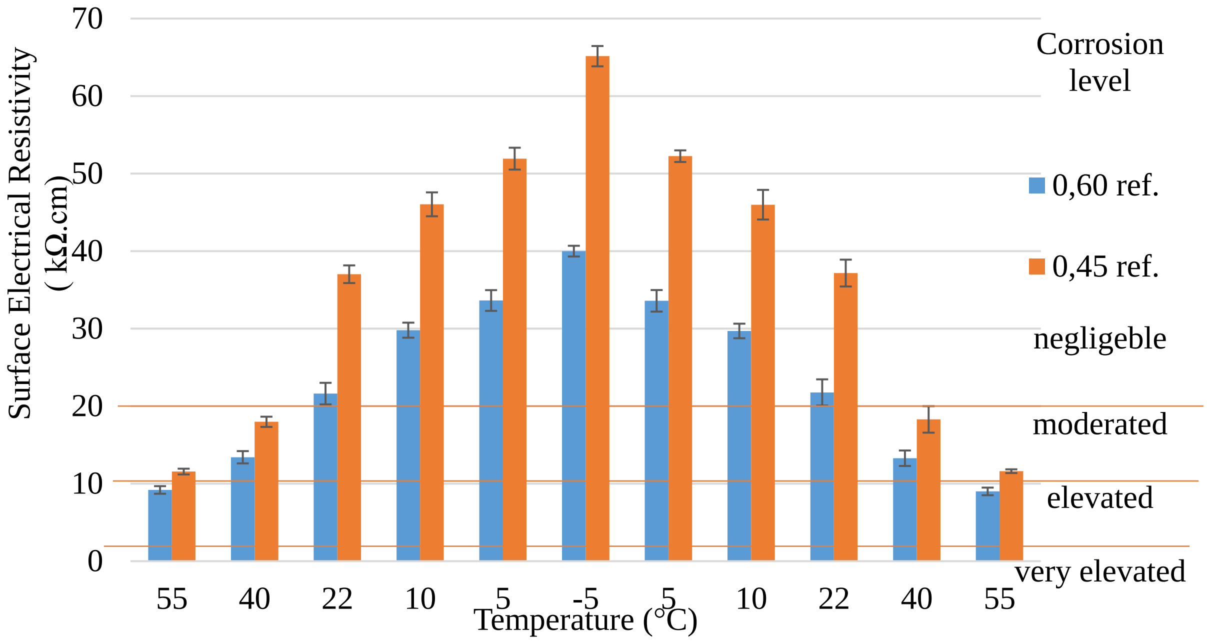

Figure 6. Surface electrical resistivity at different temperatures in samples not contaminated by chlorides (ref.).

The uncontaminated concrete showed a variation in the analysis scale for corrosion risk. At 22 °C and below temperatures, the dosages remained in the negligible risk range for both w/c ratios. Therefore, at a temperature of 40 °C, the sample with a w/c ratio of 0.45 was very close to the borderline zone between negligible and low risk of corrosion. The mix with a w/c ratio of 0.60 at a temperature of 40 °C was located in the region of low risk of corrosion and at the highest temperature in the border zone between low and high risk of corrosion.
Figure 7 presents the results of surface electrical resistivity as a function of temperature variation for dosages contaminated by chlorides.
Contaminated concretes showed similar behavior to uncontaminated concretes, following the same trend of variation in ranges throughout exposure to different temperatures.
It was possible to verify that the temperature variation influenced the electrical resistivity in an inversely proportional way; that is, as the temperature increased, the electrical resistivity of the concretes decreased.
The influence of the w/c ratio on the results was also noticed, with the highest values of electrical resistivity occurring in the sample with the lowest w/c ratio for all temperatures analyzed.

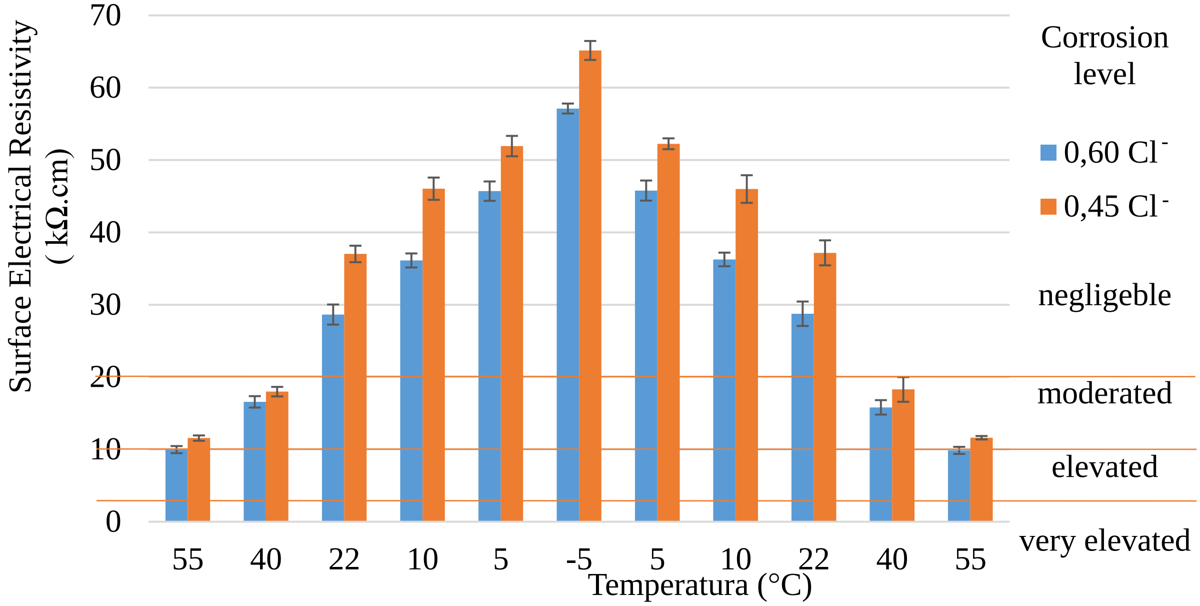

Figure 7. Surface electrical resistivity at different temperatures in mixes not contaminated by chloride (Cl^-).

4. CONCLUSIONS

Concretes with a lower w/c ratio showed greater compressive strength, lower water absorption, and a lower void ratio than concretes with a higher w/c ratio, regardless of whether or not chlorides contaminated them.
With the results achieved by the experimental program, it is possible to state with 95% significance that temperature variation influences corrosion potential, corrosion speed, and electrical resistivity. Higher temperatures resulted in more electronegative corrosion potential values and incredible corrosion speed due to decreased electrical resistivity, especially in concrete contaminated with chlorides.
At a temperature of 22 °C, the contaminated samples presented a 90% probability of corrosion for the corrosion potential, while at a negative temperature, the probability of corrosion was 10%. Uncontaminated concretes resulted in a low probability of corrosion for measurements below 22 °C. Up to a temperature of 55 °C, none of the uncontaminated samples presented a probability above 90%. At low temperatures, corrosion potential measurements indicate a low probability of corrosion, even if the reinforcement is depassivated. At high temperatures, the corrosion potential indicates the uncertainty of corrosion even if the reinforcement is passivated.
It was impossible to verify the influence of the w/c ratio on the corrosion potential results through the experimental program.
Greater corrosive activity was noticed at temperatures above 10 °C for bodies contaminated by chlorides. The corrosion speed results of the four dosages showed their greatest variation among themselves at the highest temperatures (between 40 °C and 55 °C). For values measured at negative temperature (-5 °C), it was possible to consider the values statistically equivalent through analysis of variance.
All mixes analyzed underwent variation in analytical range as the temperature changed, showing a tendency for the risk of corrosion to increase at higher temperatures.
Regarding the application of the methods used, they act in a complementary way to analyze the conditions of the structure. Moreover, due to the sensitivity of the tests, it is essential to observe environmental and climatic conditions to avoid obtaining erroneous values or interpretations during

monitoring and inspection activities.

5. ACKNOWLEDGMENTS

The authors would like to thank the Corrosion Laboratories (LabCor) of the Department of Chemical Engineering, the Civil and Mechanical Construction Materials Characterization Laboratory of the Department of Construction Materials (DEMC), and the Structural Engineering Laboratory (LAEES), all belonging to the University Federal Government of Minas Gerais. They also thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financing the project.

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