SUSTAINABLE MAINTENANCE OF AGING REINFORCED CONCRETE STRUCTURES: EVALUATING DIAGNOSTIC TECHNIQUES FOR EARLY DETECTION OF REINFORCEMENT CORROSION

MANUTENÇÃO SUSTENTÁVEL DE ESTRUTURAS DE CONCRETO ARMADO ENVELHECIDAS: AVALIAÇÃO DE TÉCNICAS DE DIAGNÓSTICO PARA DETECÇÃO PRECOCE DA CORROSÃO DAS ARMADURAS

MANTENIMIENTO SOSTENIBLE DE ESTRUCTURAS DE HORMIGÓN ARMADO ENVEJECIDAS: EVALUACIÓN DE TÉCNICAS DE DIAGNÓSTICO PARA LA DETECCIÓN TEMPRANA DE LA CORROSIÓN DE LOS REFUERZOS

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ABSTRACT
Reinforcement corrosion is a critical issue affecting the durability of reinforced concrete structures, particularly in Brazilian urban buildings now 40 to 50 years old. Sustainable management of these aging structures is essential to extend their service life and reduce the environmental impact of demolition and reconstruction. Repairing these structures, rather than demolishing them, significantly lowers the consumption of raw materials and construction waste, aligning with sustainability principles. Early corrosion detection is crucial for timely maintenance, helping preserve structural integrity and avoid unnecessary replacements, further minimizing environmental impacts. This study, part of a doctoral thesis, evaluates diagnostic techniques based on corrosion potential measurements to support sustainable infrastructure management. Full-scale reinforced concrete beams were subjected to induced corrosion using the Modified Immersion Accelerated Corrosion (CAIM) method, targeting 5%, 10%, and 15% mass loss levels. The results showed significant uncertainty in corrosion potential diagnostics at 5% and 10% mass loss, making early-stage assessments inconclusive. However, at 15% mass loss, the method produced satisfactory results, indicating its reliability at more advanced stages. The study highlights the need for more accurate diagnostic tools for early corrosion detection to promote sustainable maintenance and reduce environmental and economic costs from structural failure and replacement.

KEYWORDS
Sustainable Maintenance; Corrosion; Diagnosis; Corrosion Potential; Corrosion Acceleration.

RESUMO
A corrosão das armaduras é um problema crítico que afeta a durabilidade de estruturas de concreto armado, particularmente em edifícios urbanos brasileiros agora com 40 a 50 anos de idade. A gestão sustentável dessas estruturas envelhecidas é essencial para estender sua vida útil e reduzir o impacto ambiental da demolição e reconstrução. Reparar

essas estruturas, em vez de demolir, diminui significativamente o consumo de matérias-primas e os resíduos de construção, alinhando-se aos princípios de sustentabilidade. A detecção precoce da corrosão é crucial para a manutenção oportuna, ajudando a preservar a integridade estrutural e evitar substituições desnecessárias, minimizando ainda mais os impactos ambientais. Este estudo, parte de uma tese de doutorado, avalia técnicas de diagnóstico baseadas em medições de potencial de corrosão para apoiar o gerenciamento sustentável de infraestrutura. Vigas de concreto armado em escala real foram submetidas à corrosão induzida pelo Método de Corrosão Acelerada por Imersão Modificada (CAIM), visando níveis de perda de massa de 5%, 10% e 15%. Os resultados mostraram incerteza significativa nos diagnósticos de potencial de corrosão em 5% e 10% de perda de massa, tornando as avaliações em estágio inicial inconclusivas. Contudo, com 15% de perda de massa, o método apresentou resultados satisfatórios, indicando sua confiabilidade em estágios mais avançados. O estudo ressalta a necessidade de ferramentas diagnósticas mais precisas para a detecção precoce da corrosão, a fim de promover a manutenção sustentável e reduzir os custos ambientais e econômicos decorrentes de falhas estruturais e substituições.

PALAVRAS-CHAVE
Manutenção Sustentável; Corrosão; Diagnóstico; Potencial de Corrosão; Aceleração da Corrosão

RESUMEN
La corrosión de los refuerzos es un problema crítico que afecta la durabilidad de las estructuras de hormigón armado, particularmente en edificios urbanos brasileños de 40 a 50 años de antigüedad. La gestión sostenible de estas estructuras envejecidas es esencial para prolongar su vida útil y reducir el impacto ambiental de la demolición y reconstrucción. Reparar estas estructuras, en lugar de demolerlas, reduce significativamente el consumo de materias primas y los residuos de construcción, alineándose con los principios de sostenibilidad. La detección temprana de la corrosión es fundamental para realizar un mantenimiento oportuno, preservando la integridad estructural y evitando reemplazos innecesarios, minimizando así los impactos ambientales. Este estudio, parte de una tesis doctoral, evalúa técnicas de diagnóstico basadas en mediciones de potencial de corrosión para respaldar la gestión sostenible de infraestructuras. Vigas de hormigón armado a escala real fueron sometidas a corrosión inducida mediante el Método de Inmersión Acelerada Modificada (CAIM), con niveles de pérdida de masa del 5%, 10% y 15%. Los resultados mostraron una incertidumbre significativa en los diagnósticos de potencial de corrosión con pérdidas de masa del 5% y 10%, haciendo que las evaluaciones en etapas tempranas fueran inconclusas. Sin embargo, con una pérdida de masa del 15%, el método produjo resultados satisfactorios, indicando su fiabilidad en etapas más avanzadas. El estudio subraya la necesidad de herramientas diagnósticas más precisas para la detección temprana de la corrosión, con el fin de promover el mantenimiento sostenible y reducir los costes ambientales y económicos derivados de fallos estructurales y reemplazos.

PALABRAS CLAVE
Mantenimiento Sostenible; Corrosión; Diagnóstico; Potencial de Corrosión; Aceleración de la Corrosión

1. INTRODUCTION

In the early years of the twentieth century, civil construction underwent a significant paradigm shift. Traditional construction methods at the time predominantly relied on self-supporting masonry and metallic structures. However, the introduction of reinforced concrete brought about a transformative change. This innovative material combined the versatility and availability of concrete with the high strength of steel, offering new possibilities for construction. As a result, reinforced concrete technologies began to rise in prominence, marking the beginning of a new era in construction that started in the early decades of the last century.

Reinforced concrete structures, including buildings and bridges, are designed for longevity. Bridge structures often have a design life of 100 years or more. When the correct concrete cover is used with an appropriate mix design, the concrete typically provides adequate corrosion protection for the embedded steel reinforcement bars, Donadio, Capacho, Santander (2023).

A significant portion of this growth occurred because, in the early days, it was believed that reinforced concrete structures possessed unlimited durability and required little to no maintenance. As a result, reinforced concrete was initially heralded as a material with indefinite longevity. However, it is now understood that no construction material has such characteristics, as all materials degrade and deteriorate over time.

It is widely acknowledged that when properly designed, executed, and mixed, reinforced concrete can have a substantial lifespan. However, this longevity depends on carefully evaluating several factors, including environmental exposure conditions, protective measures, and ongoing maintenance.

The pursuit of understanding the behavior of reinforced concrete throughout its lifespan has led to numerous studies aimed at comprehending the underlying mechanisms of structural degradation. Among the various degradation processes that compromise the performance of reinforced concrete structures, reinforcement corrosion stands out as the most critical due to its frequent occurrence and severity. Corrosion of the reinforcement must be carefully monitored, as it can alter fundamental structural parameters, leading to several detrimental effects, including a reduction in the cross-sectional area of the reinforcement, concrete cracking due to the tensile stress caused by corrosion products, displacement of the concrete cover; the reduced bond between the reinforcement and concrete; and a decrease in the flexibility of the steel.

However, the phenomenological mechanism of corrosion is inherently slow, making natural observation of the process impractical for timely experimental evaluation. This has led to developing methods to accelerate the corrosion process for research purposes. One of the most widely used methods is the Modified Immersion Corrosion technique. This method accelerates the corrosion process, allowing for the experimental evaluation of its effects on reinforced concrete structures. To ensure that the results are consistent with the natural phenomenon, specific parameters are adopted to minimize discrepancies.

Reinforcement corrosion is one of the main challenges faced by Civil Engineering. According to El-Reedy (2018), this type of pathological manifestation incurs billions of dollars in worldwide costs. A concerning factor, as noted by Cascudo (1997) and Ribeiro (2018), is that a significant portion of buildings and infrastructure in Brazilian urban centers were constructed during the 1970s and 1980s. As a result, many of these structures are now between 40 and 50 years old and are reaching a stage where repairs and maintenance are becoming routine. Consequently, issues related to reinforcement corrosion are expected to become more pronounced in the coming years.

The preservation and maintenance required to prevent the deterioration of the built environment involve substantial costs due to the complexity of the technologies and processes involved in rehabilitation and repair. Buildings and infrastructure are critical components of developed societies, and ensuring their usability while maintaining the highest safety standards is an indisputable priority (Andrade, 2019). Therefore, there is a growing need to evaluate corrosion at various levels of degradation, establish correlations with diagnostic techniques such as corrosion potential, and support the detection of corrosion in structures.

2. CORROSION IN REINFORCED CONCRETE STRUCTURES: EFFECTS ON STRUCTURAL BEHAVIOR

The study of corrosion in reinforced concrete is a prominent research focus within the Structural Models Testing Lab Research Group (LEME) and the Graduate School Program in Civil Engineering (PPGEC) at the Federal University of Rio Grande do Sul (UFRGS). This chapter briefly reviews the effects of corrosion on reinforced concrete structures, particularly concerning their structural behavior.

Reflecting on the history of PPGEC/UFRGS, several comprehensive works have delved into the topic of corrosion, including studies by Andrade (1992), Andrade (2001), Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019). Beyond these contributions, there exists an extensive bibliography on the subject, featuring works by Cascudo (1997), Helene (1993), Helene (1986), Meira (2017), Mehta and Monteiro (2014), Ribeiro and Cunha (2014), Tuutti (1982), among others.

2.1 Corrosion Degree in Reinforced Concrete Structures: General Considerations

Research conducted by Apostolopoulos (2007), Caprili and Salvatore (2015), Fernandez *et al.* (2015), Gehlen and Weirich (2016), and Kashani *et al.* (2015) has evaluated the influence of corrosion on reinforcement bars in steel structures, both embedded in and separate from concrete. The findings consistently confirm that corrosion adversely affects the mechanical properties of steel. Specifically, corrosion directly reduces the tensile strength of steel while simultaneously causing fragmentation, which in turn leads to reduced flexibility. From a structural behavior perspective, flexibility is highly desirable, as its absence can result in brittle failure and, often, unpredictability. In reinforced concrete structures, where steel is responsible for ensuring flexibility, corrosion levels are expressed as mass loss exceeding 5%, impacting strength and flexibility significantly. These adverse effects become more pronounced when corrosion levels surpass 10%.

It is important to note that these effects have been observed in studies focusing solely on the impact of corrosion on isolated steel bars. However, the effects of corrosion in reinforced concrete structures tend to be more severe due to the additional reduction in bond strength between the reinforcement and the concrete. Almusallam *et al.* (2001), Graeff (2007), and Caetano (2008) have reported that bond strength decreases sharply when corrosion levels reach or exceed 10%, whereas, at lower levels (1.5% to 4.0%), there may be an increase in bond strength between the two materials.

When analyzing corrosion in reinforced concrete structures, particularly in elements subjected to bending, such as beams, a similar pattern of behavior is observed. Even at a corrosion level of 5%, there is a noticeable reduction in the structural performance of these elements. However, the decrease in structural performance becomes significantly more severe when corrosion levels exceed 10%. This intensified effect can be attributed to the reduction of steel's mechanical properties and the loss of bond strength between the concrete and steel

2.2 Corrosion Mechanism in Reinforced Concrete Structures

Tuutti (1982) proposed a phenomenological model for the corrosion mechanism in reinforced concrete reinforcements, dividing the process into two stages: start and propagation. According to Cascudo (1997), the development of corrosion requires the rupture of the steel's passive layer. Andrade (2001) defines the start process as the time for aggressive agents, such as carbon dioxide or chlorides, to penetrate the concrete cover and break the reinforcement’s passive layer.

Once the passive layer is breached, the reinforcement becomes vulnerable to corrosion, marking the beginning of the propagation stage (Cascudo, 1997). During this phase, as noted by Meira (2017), the corrosion process advances, leading to the kinetics of corrosion. This stage is where the harmful effects of corrosion manifest. Based on studies conducted within this research, which focus on the propagation stage, the primary harmful effects of corrosion in reinforced concrete structures are introduced and discussed.

The effects of corrosion in reinforced concrete structures can be categorized into three main consequences: the mechanical properties of the reinforcements, the bond between the reinforcements and the concrete, and the fissuring of the concrete. A key concern in the literature is the loss of monolithic behavior in the structure, which reduces its load-bearing capacity.

Additionally, the weakening of steel during the corrosive process is frequently discussed, as it diminishes the steel's ability to deform under load. Consequently, the relative impact of corrosion on the structural behavior of reinforced concrete is primarily developed around the themes of the mechanical properties of the reinforcements and the loss of bond strength between the concrete and the reinforcement (Reginato, 2020).

Reinforcement plays a crucial role in reinforced concrete structures. The amount of reinforcement is determined through often complex calculations and is typically expressed in terms of the necessary reinforcement area. Thus, the reinforcement area is one of the most critical parameters in reinforced concrete structures (Graeff, 2007).

During the corrosion propagation stage, corrosion products (such as oxides and iron hydroxides) form, consuming the reinforcement's mass. This results in material loss and a consequent reduction in the reinforcement's cross-sectional area.

Corrosion can significantly impact the tensile strength and flexibility of the reinforcements. These properties are essential for structural performance, affecting the structure's load-bearing capacity and failure mode (Meira, 2017).

3. NONDESTRUCTIVE METHODS FOR THE EVALUATION OF CORROSION

Over the past few decades, the application of Nondestructive Testing (NDT) in Civil Engineering has garnered significant interest in many countries (Lorenzi *et al.*, 2015). The use of NDT in this field is closely tied to the reliability of the methods, the understanding of their application, and their economic viability (Beutel *et al.*, 2006).

Since corrosion is one of the most common degradation mechanisms in reinforced concrete structures, various NDT techniques have been developed to evaluate it. Notable among these are the corrosion potential technique, resistivity measurements, and corrosion rate assessments.

3.1. Corrosion Potential

The measurement of reinforcement corrosion potential involves recording the voltage difference between the reinforcement and a reference electrode, which is in contact with the concrete surface. This is primarily a qualitative technique that provides information about the likelihood of corrosion occurring in the analyzed reinforcement. The testing procedure is guided by ASTM C-876 (2015), the Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. This standard establishes a correlation between potential difference intervals relative to a Cu/CuSO4 (Copper/ Copper Sulfate) reference electrode and the probability of corrosion, as shown in Table 1.

Potential Difference (p.d.)	Corrosion Probability
p.d. > -200 mV	Corrosion probability smaller than 10%
-200 mV ≤ p.d. ≤ -350 mV	Uncertain corrosion probability 50%
p.d. < -350 mV	Corrosion probability greater than 90%

Table 1: Correlation Between Potential Difference Values and Corrosion Probability.
Source: Adapted from ASTM C-876, 2015.

3.2. Resistivity

Concrete resistivity is a critical parameter in the corrosion of reinforced concrete structures. High resistivity concrete significantly reduces the likelihood of reinforcement corrosion. Electrical resistivity is determined by measuring the potential differences on the concrete surface caused by applying a small current (Mehta e Monteiro, 2014).

Table 2 presents the recommendations of the Comité Euro-International du Béton, as outlined in CEB 192 (1988), which relate concrete resistivity to the probable corrosion rate.

Several techniques are available for evaluating resistivity, including the external electrode method. This method involves placing a disc-shaped metallic electrode on the concrete surface and connecting it to the reinforcement bar. The resistivity is then measured between the disc and the steel bar. This method follows the RILEM TC 154 recommendation (Elsener *et al.*, 2003).

Concrete's Resistivity (Ω.m)	Probable Corrosion Rate
> 200	Negligible corrosion probability
100 a 200	Low corrosion probability
50 a 100	High corrosion probability
< 50	Very high corrosion probability

Table 2: Correlation Between Resistivity Values and Corrosion Probability.
Source: Adapted from CEB 192, 1988.

3.3. Corrosion rate

Quantitative information regarding the steel corrosion rate is crucial for evaluating repair methods, predicting lifespan, and assessing the structural integrity of elements affected by corrosion. One of the few techniques for this purpose is the polarization resistance method (Bertolini *et al.*, 2004). The RILEM TC 154-EMC recommendation outlines the testing procedure for determining the corrosion rate of reinforcement in reinforced concrete structures through polarization resistance (Andrade, 2001).

This method provides two critical characteristics related to corrosion: the instantaneous corrosion current density (Icorr) and the corrosion rate (Vcorr). Both metrics are essential for evaluating the risk of corrosion. The current density (Icorr) is typically expressed in $\mu A/cm^2$, where values below 0.1 indicate negligible corrosion, while values greater than 1.0 suggest a high risk of corrosion.

The corrosion rate (Vcorr) represents the volumetric loss of steel per unit area and time, usually expressed in mm/year. This value is derived from the current density (Icorr) using Faraday's Law. The corrosion rate for an Icorr of 1 $\mu A/cm^2$ is approximately 0.0116 mm/year, assuming uniform corrosion. This value can also be correlated with a specific degree of corrosion (Bertolini *et al.*, 2004).

Table 3 presents the detailed relationship between current density and corrosion rate, as detailed in Andrade *et al.* (2004).

Current's density - Icorr ($\mu A/cm^2$)	Corrosion's speed - Vcorr (mm/year)	Degree of corrosion
≤ 0,1	≤ 0,001	negligible
0,1 a 0,5	0,001 a 0,005	low
0,5 a 1,0	0,005 a 0,010	moderate
> 1,0	> 0,010	high

Table 3: Correlation Ranges of Current Density and Corrosion Rate Values Relative to Armature Service Life Significance.
Source: Adapted from ASTM C-876, 2015.

4. EXPERIMENTAL PROGRAM

The experimental program is organized into three phases: molding, corrosion acceleration, and evaluation through NDT testing. The study is designed around a comparative analysis of the effects of corrosion on entire structural elements, explicitly comparing those that did not experience any harmful effects of corrosion. The detailed structure of the experimental program is illustrated in Figure 1, which outlines the different steps undertaken in the study.

Table 4 presents the terminology of the beams used throughout the experimental study, aligning with its development phases. Two beams were utilized for each combination.

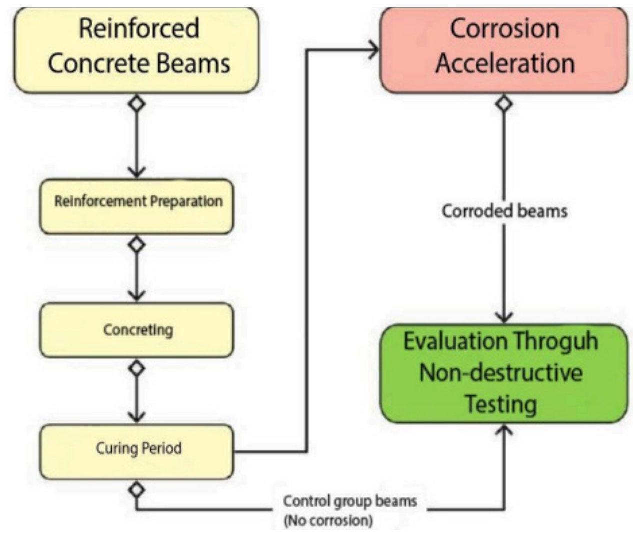

Figure 1: Experimental program's detailing.
Source: The authors.

Degree of Corrosion	Nomenclature*
0% (Reference)	COR-0-V1
	COR-0-V2
5%	COR-5-V1
	COR-5-V2
10%	COR-10-V1
	COR-10-V2
15%	COR-15-V1
	COR-15-V2
* V1 and V2 refer to samples 1 and 2 for each nomenclature	

Table 4: Combinations and beam nomenclature.
Source: The authors.

4.1. Structural Design of Reinforced Concrete Beams

To approximate the study conditions to those of actual urban constructions and coastal environments, concrete with a characteristic compressive strength of 30 MPa was selected. This strength level is the minimum NBR 6118 (2014) required for Environmental Aggressiveness Class III (CAAIII). This choice reflects the common usage of concrete with compressive strengths between 20 and 30 MPa in general building construction. Additionally, concrete with higher compressive strength is less susceptible to reinforcement corrosion.

This is due to its lower porosity, which impedes the transport of oxygen and moisture, thereby reducing the passage of electrical current and slowing the corrosion process, Caetano (, 2008); Graeff (2007), Stein (2019).

Regarding the geometry, the dimensions were determined based on important considerations, as discussed in Almusallam (2001). All beams have a cross-sectional area of 15 cm (width) x 30 cm (height) and a length of 300 cm. The lower longitudinal reinforcement consists of two CA-50 steel bars, each with a diameter of 12.5 mm, anchored with hooks at the ends. The upper reinforcement also uses CA-50 steel, with a diameter of 6.3 mm. The transverse reinforcement consists of stirrups with a diameter of 6.3 mm, spaced uniformly at 7 cm intervals. The reinforcement has a concrete cover of 1.5 cm. The detailed design of the reinforced concrete beams is illustrated in Figure 2

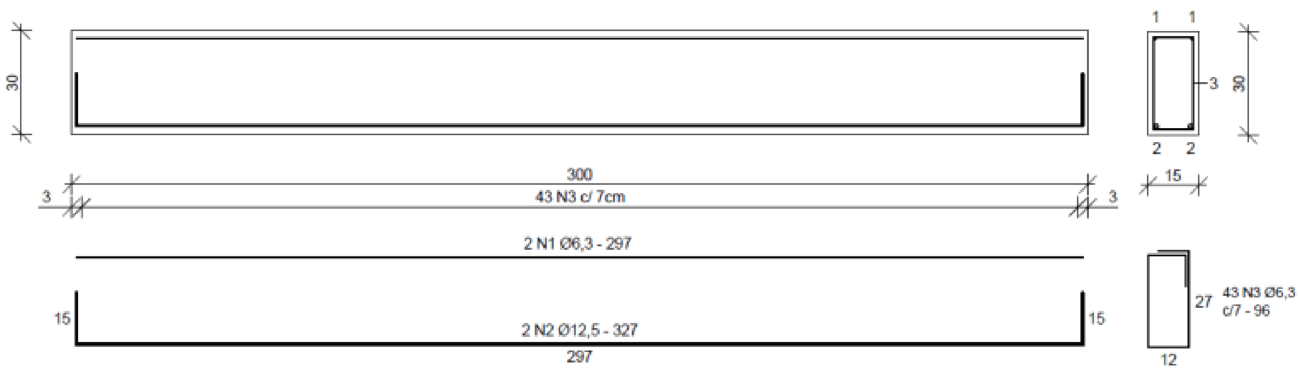

Figure 2: Reinforcement Detailing of Reinforced Concrete Beams.
Source: The authors.

4.2 Materials

The company responsible for producing the reinforced concrete beams provided the materials used in this research. The following materials were employed: Portland cement CPV-ARI, natural sand (fine and medium), basaltic gravel (types 1 and 0), and a superplasticizer additive.

The beams were concretized at a precast factory in Porto Alegre, RS. For this purpose, a computerized concrete batching plant with mass dosing was utilized. All beams were cast using concrete from a single batch, ensuring consistency in the mix composition. Table 5 details the concrete mix composition used in this study.

Cement (kg/m^3)	Thin sand (kg/m^3)	Medium sand (kg/m^3)	Gravel 0 (kg/m^3)	Gravel 1 (kg/m^3)	Water(kg/m^3)	Additive (l/m^3)	Relation a/c
271	280	654	231	692	185	0.8	0.68

Table 5: Description of the Concrete Mix Used in the Execution of Reinforced Concrete Beams.
Source: The authors.

The beams were analyzed at 502 days of age, exhibiting an average compressive strength of 32.4 MPa and an elasticity modulus of 34.8 GPa. This analysis was selected to eliminate the influence of compressive strength variation on the experimental results. This criterion was necessary because different degrees of corrosion required varying acceleration periods (ranging from 10 to 45 days). Stabilizing compressive strength was crucial to ensure that the analyses exclusively reflected the effects of corrosion on structural performance.

The steel used for both positive and negative reinforcement was CA-50. For the positive reinforcement, with a diameter of 12.5 mm, the average yield stress was 670 MPa, and the tensile strength was 770 MPa. The negative reinforcement, with a diameter of 6.3 mm, showed an average yield stress of 650 MPa and a tensile strength of 765 MPa.

4.3. Accelerated Corrosion

As mentioned, the corrosion acceleration method was adopted as the CAIM (Modified Immersion Accelerated Corrosion) testing. Lima [34] developed the CAIM method, building on the studies of Varela and Espinosa (1988). Many researchers have successfully employed it at LEME, such as Adamatti (2016), Caetano (2008), Graeff (2007), Stein (2019), Kirchheim *et al.* (2005), Marchesan *et al.* (1997), Selistre *et al.* (1997), and Torres (2006).

This method induces corrosion through electrochemical stimulation by applying a potential difference (p.d.) or current (i) in a chloride-rich environment. Based on the studies by Graeff (2007) and the discussions presented by Caetano (2008), the decision was made to use a constant current stimulus for electrochemical induction.

One of the critical parameters influencing this method is the current density used to accelerate corrosion. El Maaddawy and Soudki (2003) suggest that specific current density ranges are more appropriate for accelerating corrosion in reinforced concrete reinforcements. High corrosion current densities (above 500 μA/cm²) can distort the corrosion mechanism (Graeff, 2007). When the current density is too high, corrosion products do not have sufficient time to settle into the concrete's pores, leading to increased tension levels that cause fissuring inconsistent with naturally occurring phenomena in structures.

In the CAIM method, chlorides are introduced into the immersion water. To simulate natural conditions, sodium chloride was dissolved in the immersion water at a concentration of 35 g/l, creating a saline solution with a chloride concentration similar to that of the Atlantic Ocean, which borders the Brazilian coast, Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019)

To ensure the presence of oxygen and moisture, essential for developing the corrosive process, the reinforced concrete beam is submerged up to the lower face of the longitudinal reinforcement, as shown in Figure 3. In the solution, both a negative and a positive electrode, made of stiff copper wire with a diameter of 2.5 mm, are placed. The positive electrode is positioned 3 mm above the longitudinal reinforcement. To prevent contact between the electrode and the reinforcement, the electrode is encased in a U-shaped butyl rubber sheath, as illustrated in Figure 3.

Since the current rate is proportional to the corroded surface area of the reinforcement, both the longitudinal reinforcements and a portion of the transverse reinforcements were considered. The longitudinal reinforcement was accounted for (297 cm long), with an additional 2.5 cm for each anchoring hook—equivalent to twice the reinforcement's diameter. The transverse reinforcement was considered in two portions: one below the longitudinal reinforcement and another extending 2.5 cm above the longitudinal reinforcement, equivalent to twice the longitudinal reinforcement's diameter.

Finally, the reinforcement intended for corrosion had a mass of 7,800 g and a surface area of 3,878 cm² exposed to the corrosive process, considering both the longitudinal and a portion of the transverse reinforcement. Using power supplies, each beam's current of 1.94 A was applied based on a current density of 500 μA/cm².

Each power supply featured two outputs capable of providing either constant current or voltage, with current ranging from 0 to 3 A and voltage ranging from 0 to 30 V.

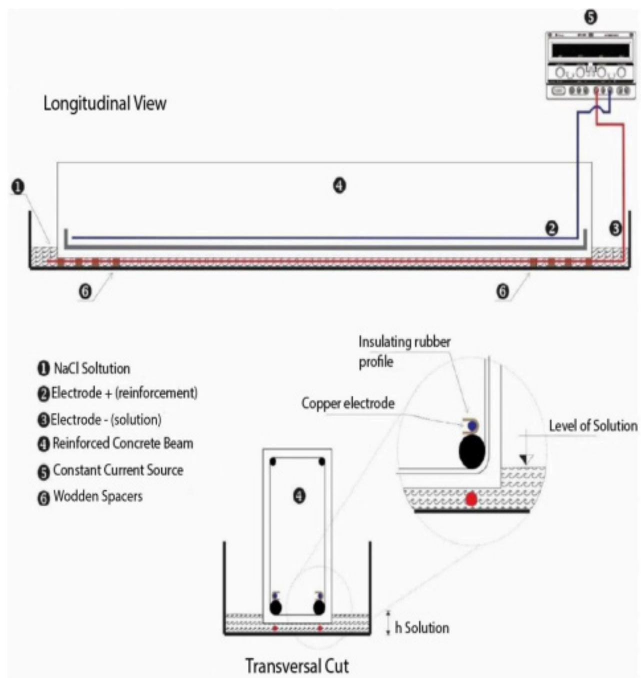

Figure 3: Layout Adapted for Corrosion Acceleration.
Source: The authors.

To achieve the desired degrees of corrosion, a theoretical approach based on Faraday's Laws was employed to predict mass loss and, consequently, the degree of corrosion.

This theory has been utilized by various authors such as Helene (1997), Adamatti (2016), Caetano (2008), Graeff (2007), and Stein (2019). The degree of corrosion predicted by Faraday's Law corresponds to the area under the curve of current versus time. In cases where corrosion is accelerated by applying a constant current, this area can be approximated as a rectangle.

Thus, the degree of corrosion is calculated by determining the mass loss using Faraday's Law, as expressed in equation (1):

$$\Delta m = \frac{M \times I \times t}{z \times F} \quad (1)$$

Where Δm = mass of consumed steel (g); M = metal's atomic weight (56 Fe); I = current applied (A); t = corrosion acceleration time (s); z = ionic charge (= 2); F = Faraday's constant (=96500A/s).

As the researchers describe, extended test times are necessary to achieve the desired degrees of corrosion beyond those predicted by the simple application of Faraday's Law. Due to this, the methodology proposed by Graeff [10] is applied for calibrating the corrosion degrees, and the values presented by Stein [11] are utilized.

Therefore, using equation (2), the predicted time required for corrosion is determined based on the mass loss necessary to reach the intended degree of corrosion:

$$tc = \left[\left(\frac{\Delta m.z.F}{M.I}\right) 1,1778\right] + 357825 \quad (2)$$

Where tc = time of corrosion (s).

4.4. Corrosion Potential

First, it is essential to locate the reinforcement bars to determine the corrosion potential. This was achieved using a cover meter detection device, specifically the PROFOMETER 600 model, as shown in Figure 4.

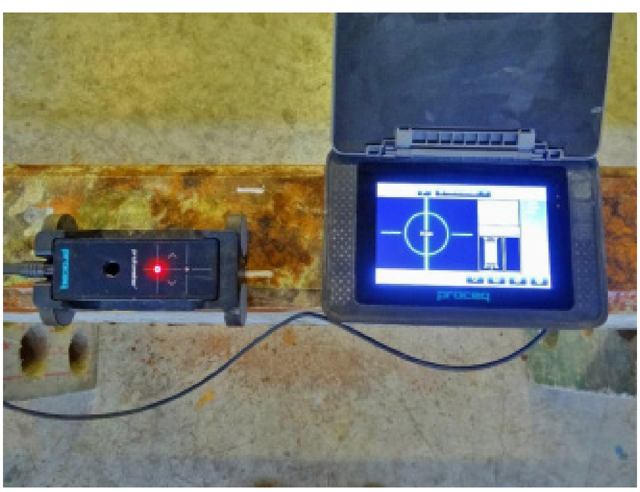

Figure 4: Locating reinforcements through a cover meter and marking the reading grid for NDT evaluation.
Source: The authors.

The corrosion potential testing procedure follows ASTM C-876 [28], which establishes a correlation between potential difference intervals measured against a reference electrode made of Cu/CuSO4 (Copper/Copper Sulfate) and the probability of corrosion.

The GECOR 8 equipment, equipped with a Cu/CuSO4 reference electrode, was used to conduct the test. The negative pole of the device is connected to the electrode. In contrast, the positive pole is connected to the reinforcement bar via a copper wire attached to the reinforcement before concreting.

The electrode is then positioned on the concrete surface, ensuring an electrical connection with the reinforcement bar. Figure 5 illustrates the method's application and the equipment setup.

The evaluation was conducted by mapping the corrosion potential for each analyzed beam. Measurements were taken along the longitudinal reinforcement bars, with a 25 cm spacing between each reading point.

4.5. Evaluation of the Degree of Corrosion

The beam reinforcements were extracted, as shown in Figure 6. The region near the support was chosen for this retrieval. Reinforcements were extracted from all beams, including those that did not undergo a corrosive process, to serve as a control group for determining the degree of corrosion.

Figure 5: Determining the corrosion potential with the GECOR 8 equipment.
Source: The authors.

After the beam reinforcements were retrieved, the concrete adhered to the bars was removed. The reinforcements were then immersed in a solution of 3.5 g hexamethylenetetramine, diluted in a mixture of hydrochloric acid (500 ml) and distilled water (500 ml).

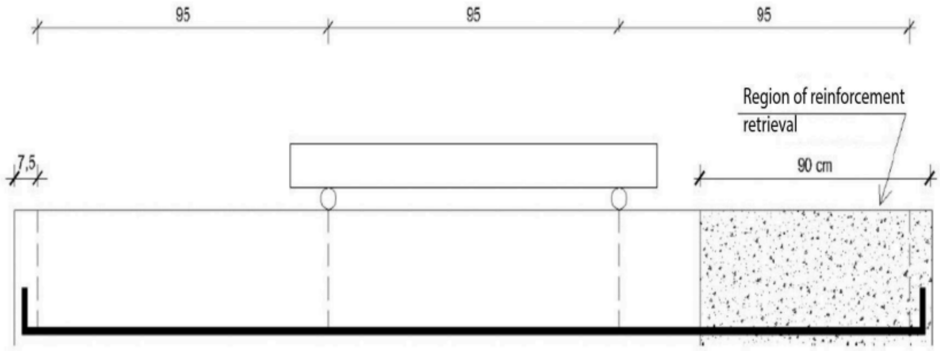

Figure 6: Region of beam reinforcement retrieval, distances in centimeters.
Source: The authors.

This procedure follows the ASTM G1-03 standard (2017). The bars were kept in the solution for 40 minutes to remove the corrosion products. Afterward, they were rinsed in running water to remove residual hydrochloric acid. Following the cleaning, the bars were placed in an oven set at 30°C until all moisture was removed. Once dry, the mass and length of each bar were measured to determine the linear mass. The degree of corrosion, expressed as mass loss, was calculated using Equation (3).

The reference linear mass was taken as the average of the non-corroded reinforcements.

$$GC = \frac{(m_{ref} - m_{cor})}{m_{cor}} x\, 100 \qquad (3)$$

Where GC = Degree of corrosion, expressed in mass loss; mref = average linear mass of non-corroded reinforcement; mcor = individual linear mass to corroded reinforcement.

After the tests, the longitudinal reinforcement bars were extracted from each beam to determine the actual degree of corrosion, following the procedure outlined in ASTM G1-03 (2017).

Due to possible differences between theoretical and actual corrosion, the results were evaluated within various variations. The adopted ranges reflect the practical evaluation of corrosion. The mass loss percentage was determined using average values, with two reinforcement bars analyzed for each beam. Table 6 shows the actual degree of corrosion for one of the beams.

According to Table 6, the actual corrosion values were close to the predicted values established in the experimental program when comparing the average values for each group of corroded beams. The exception was at 5%; the corrosion was 1.27% below the predicted outcome. This discrepancy may be attributed to concrete pore clogging, which occurs early in the corrosion acceleration process, requiring an adaptation period for the expected corrosion level to be reached.

5. RESULTS AND DISCUSSIONS

5.1. Accelerated corrosion

The accelerated corrosion was conducted following the parameters and methodology described in Section 4. All beams that underwent corrosion during the acceleration process exhibited the following behavior. As the corrosion process progressed—using an electrical circuit formed between the solution and the corrosion electrode, powered by a constant current—it was observed that the current did not remain constant. The current decreased early in the acceleration process (within the first 3 to 5 days). Then, it returned to its initial level after 1 to 2 days, remaining constant for the tests.

This behavior is related to the kinetics of the corrosive process, a phenomenon known as concrete pore clogging.

5.2. Corrosion diagnosis through non-destructive methods: Corrosion potential

The measurement of corrosion potential is a widely used qualitative technique that provides data on the likelihood of corrosion in the analyzed reinforcement. The testing procedure was conducted following ASTM C-876 (2015). The corrosion potential values in Table 7 represent the average for each beam and the corresponding standard deviation. These parameters are also related to the probability of corrosion for each level of corrosion (beam group).

As expected, a decrease in corrosion potential was observed as the level of corrosion increased. When comparing the acquired data with the value ranges specified in ASTM C-876 (2015), it was found that for the control group (COR-0), the probability of corrosion was below 10%. The results were uncertain for the corroded beams at the 5% and 10% levels (COR-5 and COR-10). However, for the 15% corrosion level (COR-15), the probability of corrosion was greater than 90%.

It was noted that the corrosion measurements using the corrosion potential technique for the 5% and 10% levels were uncertain. At both levels, the corrosion potential remained within the same reading range and was classified with a 50% chance of corrosion occurrence.

Nevertheless, despite the uncertainty, corrosion was confirmed by measuring reinforcement mass loss, even if it was not visually apparent.

Therefore, the evaluation of corrosion using the corrosion potential method showed limited efficacy in diagnosing corrosion for levels up to 10%. However, it was more reliable for levels around 15%. Despite these findings, the corrosion potential test did not consistently produce safe results. It suggests that while it can be used for diagnosing corrosion, it should be applied cautiously as it may yield potentially unreliable outcomes.

In addition to the statistical data on corrosion potential presented in Table 7, a potential mapping for each beam was conducted, as shown in Figure 7. This mapping was created by elaborating hypsometric curves using data interpolation with the minimum curve technique.

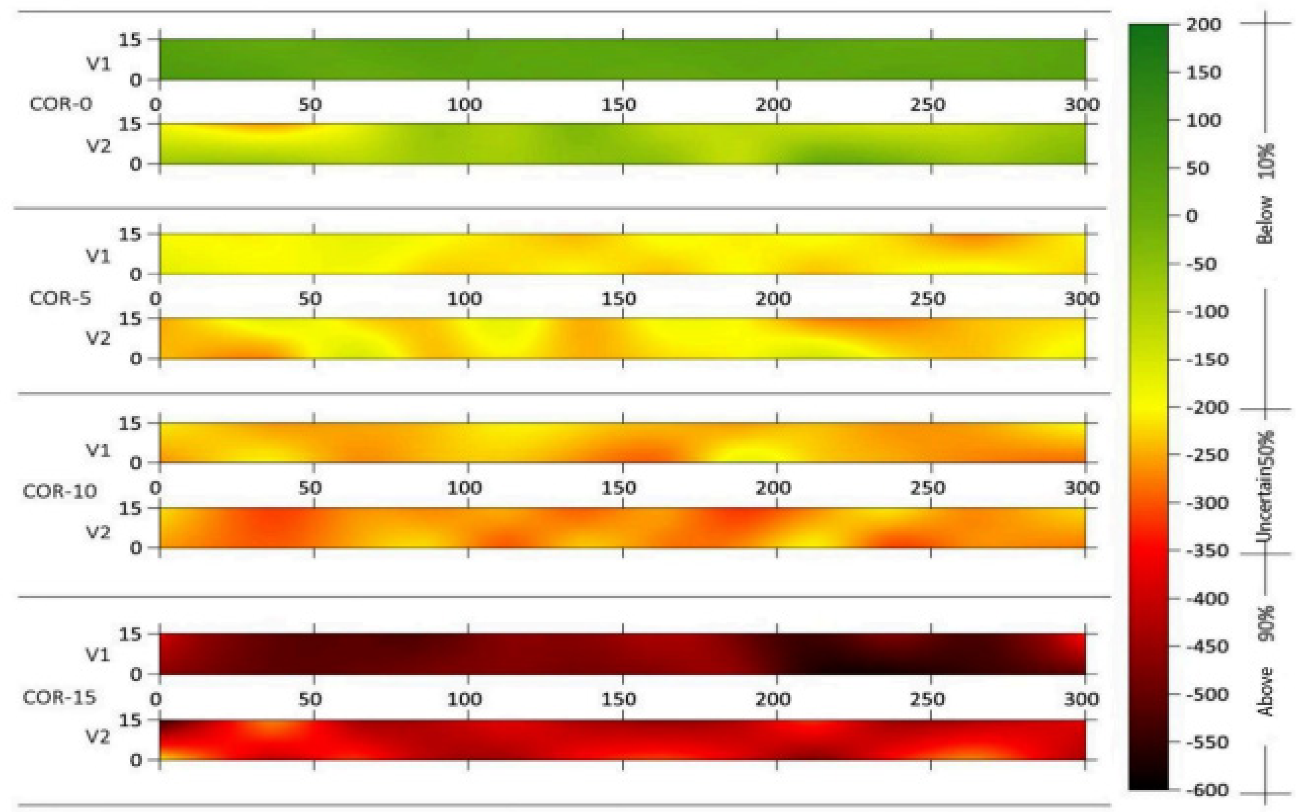

Figure 7: Corrosion potential mapping, distance in centimeters.
Source: The authors.

This interpolation technique utilizes a polynomial to create a surface that minimizes curvature. This results in a smoother surface that passes through the sampled points, accurately reproducing the variable values. The interpolation and mapping were generated using image processing software (Andriotti, 2009).

The scale used for the mapping was based on ASTM C-876 (2015) parameters, which express corrosion potential in millivolts (mV) and relate these values to the probability of corrosion. The corrosion potential mapping, illustrated in Figure 7, provides a global visualization rather than just a numerical parameter. It was observed that the potential was uniform for each of the analyzed beams and that there was a consistent relationship between potential and the beam groups. This mapping graphically demonstrates that corrosion potential decreases as the corrosion level increases—the higher the level of corrosion, the lower the corrosion potential.

6. CONCLUSIONS

This research assessed potential corrosion techniques to diagnose corrosion in reinforced concrete beams, focusing on sustainability in materials durability and long-term structural integrity. The key findings regarding the corrosion acceleration process are summarized as follows:

a) The accelerated corrosion technique, applied to reinforced concrete beams through CAIM testing, effectively advancing the corrosion process sustainably and efficiently.

b) The average corrosion degree closely matched the theoretical values outlined during the experimental program design, ensuring accurate and predictable outcomes supporting sustainable infrastructure maintenance.

CAIM testing confirmed the efficacy of the accelerated corrosion technique in reinforced concrete beams. By adjusting corrosion time using the methodology proposed by Graeff (2007) and integrating values from Stein (11), a strong correlation was established between the theoretical and empirically obtained degrees of corrosion. This highlights that the corrosion acceleration procedure used in this research was adequate and sustainable, effectively optimizing time and resources.

Regarding the corrosion diagnosis technique using non-destructive testing (NDT) through corrosion potential, the study revealed uncertainties in the measurement at 5% and 10% corrosion levels. Both levels had similar corrosion potentials, with a 50% probability of corrosion occurrence, indicating limitations in precision for lower corrosion rates. The corrosion potential method, however, proved effective at diagnosing corrosion at the 15% level, where sustainable monitoring practices can be more reliably implemented.

In conclusion, while corrosion potential testing may not consistently deliver consistent results, it remains a viable diagnostic tool when applied cautiously in sustainable practices. For enhanced accuracy, especially for corrosion levels with a mass loss between 5% and 10%, it is recommended that additional diagnostic techniques be employed simultaneously to ensure the long-term durability and sustainability of reinforced concrete structures.

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ANNEX 1

Beam	Theoric corrosion degree	Real corrosion degree	Average corrosion degree	Intended corrosion degree
COR-5-V1	5,03%	3,49%	3,73%	5%
COR-5-V2	5,09%	3,97%		
COR-10-V1	10,17%	9,97%	10,05%	10%
COR-10-V2	10,14%	10,13%		
COR-15-V1	15,65%	14,20%	13,87%	15%
COR-15-V2	15,46%	13,55%		

Table 6: Actual Corrosion Degree Obtained Empirically Compared to Theoretical Values.

Source: The authors.

Beam Group	Beam	Av. (mV)	SD (mV)	Group Av. (mV)	Group SD (mV)	Corrosion Probability
COR-0	V1	28,84	7,45	-30,78	25,24	Below 10%
	V2	-90,40	43,03			
COR-5	V1	-298,22	21,34	-257,57	22,59	Uncertain 50%
	V2	-216,92	23,85			
COR-10	V1	-240,96	17,95	-252,99	19,71	Uncertain 50%
	V2	-265,03	21,47			
COR-15	V1	-494,11	32,94	-438,42	33,01	Above 90%
	V2	-382,72	33,08			

Table 7: Average and Standard Deviation of Corrosion Potential for the Control Group and Corroded Beams.

Source: The authors.