

Evaluation of chloride ion penetration through concrete surface electrical resistivity of field naturally degraded structures present in marine environment



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HIGHLIGHTS

- Electrical resistivity of real reinforced concrete structures were analyzed.
- Electrical resistivity and chloride penetration relationship was analyzed.
- Limit values regarding chlorides penetration and electrical resistivity were proposed.

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ABSTRACT

As reinforcement corrosion due to chlorides action is the main cause degradation of reinforced concrete structures in marine environment, concrete electrical resistivity has been used as a non-destructive methodology in order to evaluate the service life of these structures, since it is a simple and fast field methodology that presents confiable results. At this point, many works have been carried out in order to establish a correlation between concrete electrical resistivity and chlorides penetration. However, observing the literature and standards about this issue it was noted significant differences between the values presented for establish this correlation. Furthermore, a significant part of the literature studies were conducted under controlled laboratory conditions, which can differ from the real aggressiveness that a structure is exposed. Thus, this paper presents a new proposal of range values and classes between the chlorides penetration and the concrete surface electrical resistivity, based on the analysis of real chloride profiles from structures present for more than 40 years in different marine aggressive zones under natural degradation. The results shown that standard parameters were close from the values proposed in this work; however a refinement in the range values and the insertion of new parameter classes are necessary for better evaluation of chlorides penetration in concrete structures present in marine environment.

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1. Introduction

In reinforced concrete structures the alkaline solution present on concrete pores promotes a suitable environment for rebars protection against corrosion. This alkaline environment (pH close to 12.5) enables the formation of a passivating film composed of Iron Oxides that cover and protect them. Nevertheless, concrete is a non-saturated porous medium and external agents such as Carbon Dioxide, in urban areas, and chlorides, in marine environment, penetrate through concrete porous network and, when reach the reinforcements ends up creating conditions to the beginning of

the corrosion process, once this agents are capable to destroy this passivating film [1–6].

As soon as reinforcement corrosion starts and progress, corrosion products are formed and accumulate around the cathode zones on bars surface. From this process radial tension are produced in relation to the bar axis leading to three main effects: first, the reinforcement cross section is gradually reduced, impacting the bars mechanical properties and reducing its tensile strength, mainly in terms of its ductility; secondly, the corrosion products settled on reinforcement surface produce tension on concrete. From this mechanism, allied to concrete limited plastic deformation, concrete cracks appear, culminating on the concrete cover spalling, potentiating the ingress of aggressive agents from the environment and, consequently, spending up the structure

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degradation process. Finally, the third point is related to the lost of the monolithism in the concrete-steel system. In this sense, the lost of the reinforcement adherence to the concrete impair the transfer of loads between structural elements [1–10].

By the exposed, reinforcement corrosion is pointed out by many researches as the main cause of reinforced concrete structures degradation, which has motivated worldwide researches on different perspectives, since the comprehension of the corrosion effects on the mechanical properties of corroded reinforcements, up to the proposal of new structures service life prediction models in different environments. In this sense, marine environment is known as one of the most aggressive where a reinforced concrete structure can be present under the corrosion perspective, due to chlorides action [1–8].

Chlorides are present not only in the sea water, but in the marine atmosphere, consequently, even structures that does not present a direct contact with sea water may be subject to reinforcement corrosion. In this way, first of all, chlorides can penetrate through concrete pores and when reach the reinforcement surface, the passivating film is locally broken, making possible the development of well defined surface corrosion points, called as pits. These pits become deeper as the corrosion process progress, reducing the reinforcement cross section and creating axis eccentricities between corroded and non-corroded bars sections. From this mechanism a progressive degradation of the bars mechanical properties, and, consequently, of the reinforced structures can be observed. It should be pointed out that corrosion process can lead structures to the collapse, considering the possibility of sudden brittle fractures of corroded bars, once one of the main impacts of corrosion on bars mechanical properties is the suppression of the yielding and plastic deformation up to fractures [5–10].

About this issue, Apostolopoulos, Demis and Papadakis (2013) [1] analyzed pit morphology and mechanical properties of bars performing corrosion accelerated tests in a saline chamber. The authors corroded bars directly exposed to salt fog and bars presented in concrete prisms. The authors observed that corrosion impacts on mechanical properties of corroded bars immersed in concrete prisms were more pronounced in relation to bars exposed directly to saline fog. Zhu and François (2014) [11] used techniques to simulate mechanically the reinforcement corrosion. The authors demonstrated that, when pitting corrosion occurs in the bars, axis eccentricities are generated between successive bars cross-section. From this mechanism, the authors concluded that higher eccentricity value conduct to lower mechanical properties of the corroded bars. In fact, the work of Imperatore, Rinaldi and Drago (2017) [12] corroborate with these previous literature results. The authors observed, by accelerated corrosion assays, that as the reinforcement corrosion degree intensify, a progressive reduction on mechanical properties of the bars are observed, mainly bars ductility.

In the perspective of structures Kashani, Crewe and Alexander (2013) [13] analyzed the impacts on buckling in corroded reinforced prisms by accelerated tests. The authors noted a reduction of 50% in the plastic strain of the prisms, even bars presenting only 10% corrosion degree.

This behavior was observed not only in corrosion accelerated assays. Balestra et al. (2016) [2] observed that even bars with low corrosion degree can present significative reductions on its mechanical properties. Besides, the authors concluded that interpretations about the effective and nominal mechanical properties of corroded reinforcement can lead to erroneous interpretations of the real mechanical properties of the corroded bars, consequently, the author's alert that care should be taken about this issue.

By means of the above, reinforcement corrosion induced by chlorides has been objective of several researches about this issue.

In this thought, one research line is related to the application of Non-Destructive Tests (NDT) in order to supply parameters related to structural security and durability. In this sense, concrete surface electrical resistivity has been driven different studies in order to provide faster and reliable parameters through a simple methodology to support durability analysis for field reinforced concrete structures [10,14–16]. It is important to mention that as reinforcement corrosion is an electrochemical process that requires electric flow, the interpretation of electrical resistivity of the medium where the reinforcements are present can provide key informations about the durability of field structures that can be degraded due to reinforcement corrosion [5,17].

The ability of the material to lead with charge flow is described by the material's electrical resistivity. This property is governed by Ohm's Law, where the resistivity is defined as the gradient between the apparent voltage and the resulting flowing current, both multiplied by a constant related to the material properties. For field concrete structures the technique based on Wenner's fourth electrodes is one of the most applied methodologies, where a current is applied by external electrodes and the voltage is measured by the internal ones [14,16,18].

Regarding the state of the art about the researches in this issue Sengul [18] describes resistivity as an indicator of concrete structures durability, presenting a correlation between chlorides diffusion coefficient for different concretes and resistivity. Horbostel et al. [19] recently presented a detailed literature review about the relationship between corrosion risk and concrete electrical resistivity.

Bem et al. [20] discussed as chemical admixtures, mineral additions and water-cement ratios can affect concrete resistivity. Medeiros-Junior and Lima [17] presented the influence of cement type and hidration time on concrete electrical resistivity. In this research, the authors monitored for 730 days the electrical resistivity of concretes made with different cement types. The authors concluded that concrete surface electrical resistivity increases over time due to the refinement of the concrete porous as a result of cement hydration, observing a significant gradient change on concrete electrical resistivity after 500 days. In this perspective, another researches [16,18–19,21] pointed out that concrete pore saturation degree present an inversely proportional relation with electrical resistivity, once the presence of water facilitate charge flow in porous medium.

The coarse aggregates effects on concrete surface electrical resistivity were recently evaluated by Hou et al. [22]. The authors used tomography images on its analysis and concluded that there is a current preference to pass through the coarse aggregates, rather than around the aggregates (in the the Interface Transition Zone (ITZ)), corroborating with other studies [21,23].

About the influence of reinforcements on concrete electrical resistivity, Garzon et al. [24] point that the presence of reinforcements can affect the electrical resistivity measurements, once the current applied can be conducted through the bars. From this perspective, the authors proposed empirical equations, based on Finite Element Method (FEM), to take into account the reinforcements influence on the interpretation of concrete resistivity parameters.

Although several works are conducted aiming to correlate the electrical resistivity with the probable corrosion risk there is still no normative protocol [19], probably due to the materials and environment intervening factors that influence this relationship. In this sense, some standards and literature works [25–29] present a correlation between the chloride ion penetration and the concrete electrical resistivity as presented in Table 1. However, it can be observed that there is a broad range of values that can lead to difficult interpretations about the real aggressiveness level that a reinforced concrete structure is subject.

Table 1

Correlation between chloride ion penetration and concrete electrical resistivity from different references.

Concrete surface electrical resistivity (kΩ·cm)		Very high	High	Moderate	Low	Very low	Negligible
Chloride penetration (% concrete)							
Reference	[25,26]	-	<12	12–21	21–37	37–254	>254
	[27]	-	<7	7–13	13–24.3	24.3–191	>191
	[28]	-	<6.7	6.7–11.7	11.7–20.6	20.6–141.1	>141.1
	[29]	-	<16	16–28	28–50	50–343	>343
	[16]	<5	5–7.5	7.5–15	15–35	>35	-

Besides, it should be stressed that many researches that lead to these parameters presented in Table 1 were conducted in controlled laboratory environment that may differ from the real conditions to which field concrete structures are exposed, especially structures in marine environment under service for years. Thus, this paper aims to contribute in the durability field presenting a proposal of values that correlate the chloride ion permeability and the surface electrical resistivity based on the analysis of chloride profiles obtained from field structures present in marine environment since 50's.

2. Experimental procedure

The local where the experimental program was developed is known as Arvoredos Island (Island coordinates are: 23.967106 South (latitude) and 46.167061 West (longitude)). It is a rocky formation located at Guarujá City, São Paulo state, Brazil, distant 1.6 km from the coast. An overview of the Island is presented in Balestra et al. (2019) [30]. The local climatic is classified as Cfa according to Köppen classification (Humid temperate climate with hot summer) [31].

Since 50's the Island was ceded for scientific purpose to Engineer Fernando Lee. In this sense, reinforced concrete structures were built in different marine aggressive zones at this Island (Tidal zone, splash zone and marine atmosphere zone) in order to support scientific researches developed in the Biological and Environmental Science between 1950 and 1978. These structures remained under natural aggressive conditions since they were built, mainly due to chlorides action that leads to severe problems due to reinforcement corrosion. In 2016 durability analysis were performed in different structures in order to develop a new chloride service life model based on Holliday Equation considering the convection zone data as described by Ref. [30]. Among this analysis, field surface electrical resistivity assays were performed in loco in these structures and after, concrete cores were extracted in order to analyze chloride profiles for durability analysis.

In this sense, field surface electrical resistivity points were defined on concrete structures surface and were evaluated by Wenner's method (Fourth points) using a portable equipment, where the space between the electrodes was 50 mm. It should be pointed that carbonation and pacometry assays were performed before the selection of surface electrical resistivity points, once carbonated structures and the presence of reinforcement can affect the electrical resistivity measurements.

By this way, carbonation tests were performed in all the structures by spraying a phenolphthalein solution in holes done by a drill with diameter of 12.7 mm and 200 mm depth according to RILEM CPC-18 [32]. The standard describes that after spraying the phenolphthalein solution, if the pink color is observed, there is an indicative that concrete is an alkaline medium and does not present carbonation front. Besides, pacometry assays were performed in order to determine the reinforcements diameter, position and depth from concrete surface (Concrete cover thickness). For this, a pacometer with detector capacity up to 150 mm

was used in all the structures, being the informations recorded directly on concrete structures surface.

After performed carbonation and pacometry assays, the structures were evaluated visually in order to define points that could be possible to perform the surface electrical resistivity values and after, at the same points, extract concrete cores with diameter of 75 mm and minimum length of 150 mm for analysis of chlorides profiles in laboratory by X-Ray Fluorescence Spectroscopy. By this way, it were defined 17 analysis points, identified by numbers, with minimum área of 400 cm² (20 × 20 cm) in different structures.

Table 2 present the structure, point identification and the predominant marine aggressive zone where the analysis points were located. It should be pointed that when reinforcements were present, the electrical surface resistivity equipment was positioned between the reinforcements and aligned with rebars direction in order to avoid reinforcement interference on electrical resistivity measurements. Furthermore, as the paint layer of some structures could affect the electrical resistivity measurements representing an insulating layer, painted structures had this layer removed before perform the surface electrical resistivity assays. In this way a sanding machine was used to remove painting layers.

After the procedures described, concrete surfaces were moistened by spraying water, in order to saturate surface concrete porous and for improve the contact between the concrete surface and the electrodes. In sequence, the electrodes were placed on the concrete surface at the 17 determined points, and the resistivity measurements were recorded.

After record the surface electrical resistivity, in the same 17 points, concrete cores were extracted, using a core drill machine. For extraction cores procedure, the minimum water as possible was used for cool the drill, in order to avoid chloride washing effects. After extraction, concrete cores were immediately

Table 2

Predominant marine aggressive zone where surface electrical resistivity assays were performed and concrete cores where extracted.

Structure	Point identification	Marine aggressive zone
A	1	Splash zone
B	2	Marine atmosphere
B	3	Marine atmosphere
B	4	Marine atmosphere
B	5	Marine atmosphere
B	6	Marine atmosphere
B	7	Marine atmosphere
B	8	Marine atmosphere
B	9	Marine atmosphere
C	10	Marine atmosphere
C	11	Marine atmosphere
D	12	Marine atmosphere/splash zone
D	13	Marine atmosphere/splash zone
E	14	Tidal zone
E	15	Tidal zone
F	16	Splash zone
F	17	Splash zone

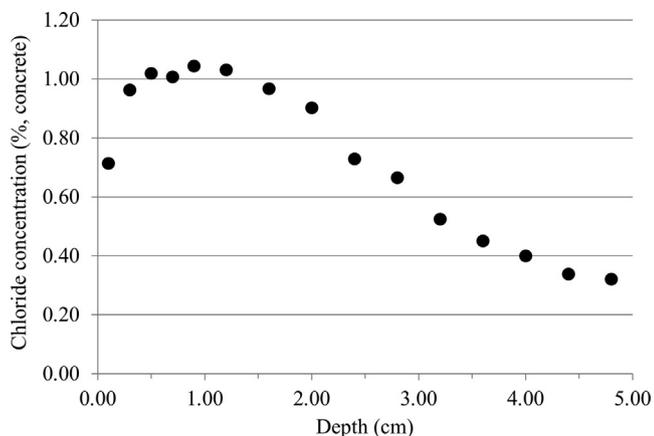


Fig. 1. Example of chloride profile obtained from concrete cores.

identified and wrapped by a plastic film, in order to avoid the carbonation effects, being transported to the Civil Construction Laboratory of the Federal Technological University of Paraná – campus Toledo for determination of chlorides concentration for analysis of chloride profiles. At laboratory, an equipment was developed for grinding the concrete cores in milimetric layers. In this sense, the first concrete cores centimeter was ground in layers of 2 mm, and between the first up to the fifth cm depth the grinding procedure was performed in layers of 4 mm. A detailed description of the grinding procedure and the equipment can be found in Refs. [30,33–35].

Each concrete powder samples, according to concrete depth that was obtained, was passed in a sieve N.200 (mesh #0.075 mm), in order to physically homogenizing the sample size, being after pressed and analyzed by X-Ray Fluorescence Spectroscopy. In this sense, a correlation equation was firstly established in order to correlate the X-Ray Fluorescence Spectroscopy and the Acid Soluble Technique described by ASTM C1152 [36]. This equation is presented in Balestra et al. (2019) [37]. After obtain all samples chloride concentration, chloride profiles were obtained as exemplified in Fig. 1. Chloride profiles are presented in Refs. [30,33,34], where it was possible to note similar chloride concentrations from other structures present in marine environment with approximately the same age as presented in Refs. [38–40].

From the chloride profiles, the sum of the chloride concentrations observed up to the fifth cm depth, called in this paper as Profile Total Concentration (PTC), was correlated with the surface electrical resistivity measurements in order to express how significant is the chloride penetration through chloride profiles. In this sense, higher PTC values indicate that chlorides can easily penetrate through concrete pores and, consequently, can reach reinforcements in short time, starting the metallic corrosion process. On the other hand, lower PTC values evince that concrete shows resistance against chlorides penetration potentially participants in the reinforcement corrosion process. From this analysis, a new proposal of values for correlation chloride penetration and surface electrical resistivity values was presented, based on real structures under natural degradation in marine environment.

3. Results and discussion

3.1. Carbonation depth, pacometry assays and definition of points for electrical resistivity measurements

The carbonation front in all the structures analyzed was limited to 1–3 mm depth from concrete surface according to the pink color observed after spraying the phenolphthalein solution, showing

that reinforcement corrosion of the structures was due to chlorides action. This behavior is justified once the Island is relatively far from the city (approximately 1.6 km from the coast) and there are many trees around the structures, reducing the CO₂ in the Island atmosphere.

About the pacometry assays, the mean concrete cover thickness observed was 29 mm (varying between 26 and 32 mm) taking into account structures present in different marine aggressive zones. Besides, rebars diameter varied between 3/8" and 1/2" and were spaced 20 cm. By these results and taking into account that corrosion was the main degradation mechanism observed at Arvoredos Island, it was possible to conclude that approximately 30 mm concrete cover is not sufficient to physical protection of the reinforcements against corrosion in marine environment.

In this sense, it should be considered that when these structures were built between 50's and 70's no standard protocol was used to take into account the particularities of built a reinforced concrete structure in different marine aggressive zones or, in other words, the same concrete cover thickness was adopted for all structures, independently if it was built at tidal, splash or marine atmosphere zone. By this way, it should be pointed that when these structures were built, the scientific knowledge about the effects of the marine environment on reinforced concrete structures under the corrosion perspective was not well documented as currently.

3.2. Surface electrical resistivity and chloride profiles analysis

The surface electrical resistivity values and the sum of chloride concentrations obtained from chloride profiles up to 5 cm depth (PTC) are shown in Table 3, whereas, Fig. 2 presents the correlation between this sum of total chloride concentration and the surface electrical resistivity values. It should be stressed first that in Fig. 2, the analysis was done considering all chloride profiles, independently if it presented or not a nitid peak of maximum chloride concentration and, secondly, PTC values are related to the percentage of chlorides in relation to the concrete mass (% concrete).

It can be seen clearly from Fig. 2 that surface electrical resistivity and profile total concentration present an inversely proportional relationship or, in other words, the higher the surface electrical resistivity values are, lower the total chloride concentrations up to 5 cm depth, presenting a moderate correlation with a R² equal to 0.58. Eq. (1) presents the relationship between the Surface Electrical Resistivity (SER), in kΩ·cm, and the Profile Total Concentration (PTC), in percentage in relation to concrete mass (%,

Table 3

Correlation between PTC and surface electrical resistivity considering all chloride profiles.

Analysis point identification	Surface electrical resistivity (kΩ·cm)	PTC (% Cl, concrete)
1	2.30	11.45
2	18.10	4.01
3	10.50	3.92
4	20.50	5.08
5	19.80	3.46
6	21.90	1.73
7	15.00	2.21
8	27.30	3.31
9	12.60	2.79
10	36.20	3.47
11	27.00	7.26
12	15.40	8.05
13	14.50	6.65
14	6.30	11.06
15	1.30	11.24
16	2.50	15.20
17	2.50	16.47

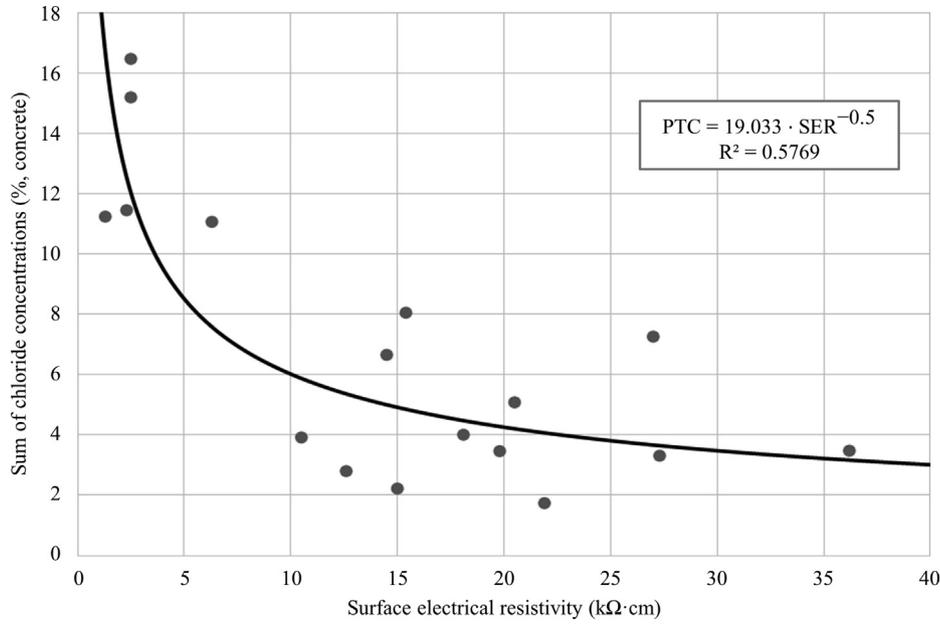


Fig. 2. Correlation between PTC and Surface Electrical Resistivity considering all chloride profiles.

concrete). Furthermore, outlier’s analysis was performed in PTC values using BoxPlot, according to Refs. [41–43]. For this, Minitab 16 Statistical Software was used. At this point, when an outlier is identified in the statistical analysis an asteristic dot is pointed. The result of the outlier’s analysis is presented in Fig. 3, where no outliers were detected. Besides, continuing the statistical analysis, potential outliers in the regression model, presented in Eq. (1), were analyzed according to Ref. [44] by studentized residuals criterion. The procedure consists in delete the “n” observations one at a time, each time refitting the regression model on the remaining “n – 1” observations. After, the observed response values are compared to their fitted values based on the models with i^{th} deleted observations; consequently, from this procedure, residuals can be analyzed. In this sense, according to the cutoff criterion of Ref. [44], an outlier is identified if the studentized residual is out the interval between –2 and 2 in absolute values. In this sense, as can be seen in Fig. 4, no outliers in the regression model were observed.

$$PTC (\%, \text{ concrete}) = \left(\frac{19.033}{\sqrt{SER} (\text{k}\Omega \cdot \text{cm})} \right) \quad (1)$$

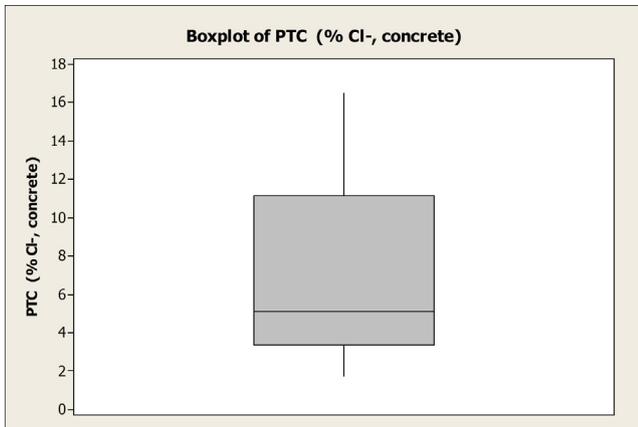


Fig. 3. Outliers analysis.

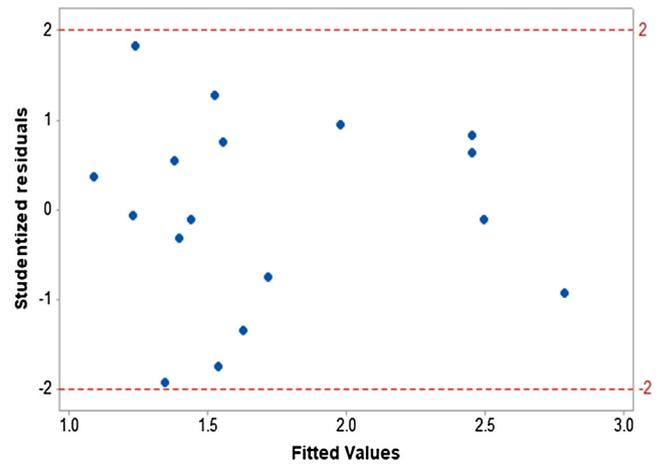


Fig. 4. Outliers analysis in the regression model.

In this way, observing Fig. 2, a significant reduction on total chlorides concentrations when resistivity values are between 0 and 5 kΩ·cm is noted, where a reduction of approximately 50% in the total chloride concentrations can be observed. After 5 kΩ·cm there is a tendency to reduction of the total chloride concentrations, however, not so pronounced as observed before 5 kΩ·cm. This behavior can be explained since concrete porosity and its electrical resistivity are related. In this way, concretes that present high volume of interconnected porous network are prone to demonstrate an easily path for charge mobility under non saturated condition and, consequently, these concretes present lower electrical resistivity values, consequently, as chlorides penetrate through concrete pores, a higher volume of interconnected porous network justify an easy path for chlorides mobility and, concomitantly, higher total chlorides concentrations can be observed in the profiles.

Even Eq. (1) presenting a value of R^2 equal to 0.5769, it can be observed that there is a decreasing relation between Profile Total Concentration (PTC) and Surface Electrical Resistivity (SER). In this sense, it should be stressed that these data were obtained from field structures under natural degradation process, whose

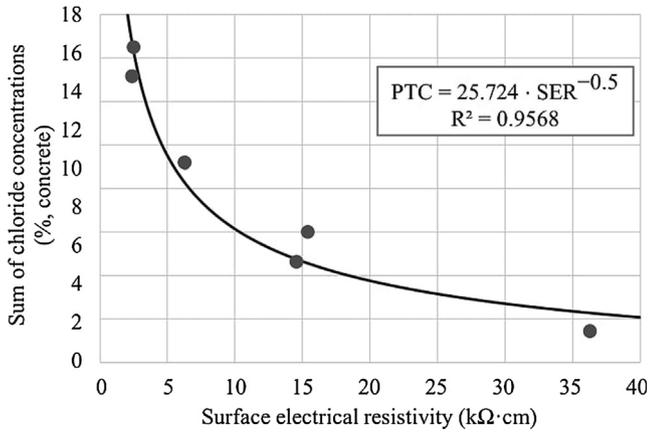


Fig. 5. Correlation between PTC and Surface Electrical Resistivity considering chloride profiles that presented sharp peak.

exposure condition differ from the controlled laboratory environment. If only chloride profiles that present a sharp peak of maximum chloride concentration were analyzed, a R^2 value equal to 0.9568 can be observed using the equation model for fit the data ($PTC = 25.724 \cdot SER^{-0.5}$) as shown in Fig. 5. The chloride profiles that presented a sharp peak of maximum concentration are presented in Refs. [30,34].

Taking the equation fitted to the data from Fig. 2 ($PTC = 19.033 \cdot SER^{-0.5}$) and its first derivate ($PTC' = -9.5165 \cdot SER^{-1.5}$) it was possible to analyze the progressive variation on total chlorides concentration as surface electrical resistivity values increase as presented in Fig. 5. By the analysis of Fig. 6 it is possible to know how difficult is to chlorides penetrate through concrete pores network by surface electrical resistivity.

Analyzing Fig. 6, it was observed that there is a significant slope on data fitted when resistivity values are between 0 and 5 kΩ·cm, demonstrating that lower electrical resistivity values can represent a higher chloride penetration through concrete pores, whereas,

between 5 and 9 kΩ·cm a change on the curve slope can be seen, indicating that there is a significant chloride penetration through concrete pores, however, in a different level from that observed between 0 and 5 kΩ·cm. Between 9 and 17 kΩ·cm the variation obtained from the first derivate of the equation fitted to the data is clear too, but is lower in comparison to the slope observed in the previous sections for lower resistivity values (<5 and between 5 and 9 kΩ·cm).

In all previously mentioned range values, the data variation of the first derivate equation fitted to the data is clear, however, between 17 and 41 kΩ·cm it can be noted that this variation is lower and, after 41 kΩ·cm, there is a tendency to asymptotic behavior. These observations lead to conclude that for surface electrical resistivity values higher than 17 kΩ·cm the chlorides penetration is lower and, after 41 kΩ·cm very low. Furthermore, progressing the analysis, it was observed that after 220 kΩ·cm the difference on the first derivate of the equation fitted to the data are less than 0.00002 showing that for resistivity values higher than 220 kΩ·cm the chloride penetration through concrete pores are negligible.

By these analyses it is possible to propose new classes and values for correlate the chloride penetration and surface electrical resistivity based on structures naturally degraded in marine environment. In this sense, as standards present this correlation stabilising the level of chloride penetration and ranges of electrical resistivity values, the same methodology and classes (very high, high, moderate, low, very low and negligible) were applied to the proposed values presented in Table 4.

For this analysis, as a significant variation on chlorides concentration was observed analyzing the first derivate of Eq. (1) when surface electrical resistivity was between 0 and 5 kΩ·cm, the value of 5 kΩ·cm was used as reference to define an upper limit to class *very high chlorides penetration*. In other words, surface electrical resistivity values less than 5 kΩ·cm represents a very high chlorides penetration in concrete. This observation is in agreement with other literature values presented in Table 1 (Ref. [16]) that observed very high chloride penetration if concrete electrical resistivity values are less than 5 kΩ·cm.

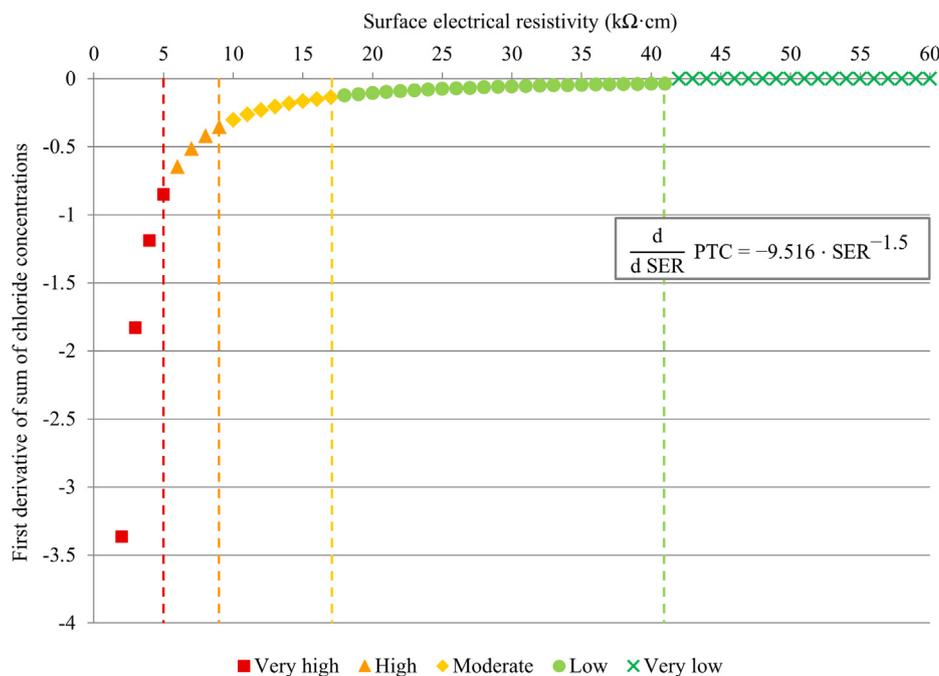


Fig. 6. First derivate of power function equation obtained from the analysis presented in Fig. 2.

Table 4

Proposed values to correlate chloride ion penetration and surface electrical resistivity.

Chloride penetration (% concrete)	Very high	High	Moderate	Low	Very low	Negligible
Concrete surface electrical resistivity (kΩ·cm)	<5	[5, 9]	[9, 17]	[17, 41]	[41, 220]	>220

In this way, 5 kΩ·cm was used as reference to determine the range values of other classes (high, moderate, low, very low and negligible) at Table 4 by Eq. (2). In this sense, knowing that exist five remaining chloride penetration classes to define ranges (high, moderate, low, very low and negligible), the “m” range values of Eq. (2) were divided in order to establish an interval of range values for these remaining classes. Furthermore, “m” in Eq. (2) expresses the gradient between the total chlorides concentration in the profiles and the total chlorides concentration in the profiles in relation to a reference (5 kΩ·cm), whereas, SER is the surface electrical resistivity values (kΩ·cm).

$$SER \text{ (k}\Omega \cdot \text{cm)} = \left(100 \cdot \frac{\sqrt{5}}{m(\%)} \right)^2 \quad (2)$$

The minimum limit values applied in this work to “m” were 75%, 55%, 35%, and 15% for *high chloride penetration*, *moderate chloride penetration*, *low chloride penetration* and *very low chloride penetration* respectively. This means that, taking 5 kΩ·cm as reference, resistivity values contained in the “m” range between 100 and 75% will be covered in the class *high chloride penetration*, whereas, resistivity values contained in the “m” range between 75 and 55% will be covered in the class *moderate chloride penetration* and resistivity values contained in the “m” range between 55–35% and 35–15% will be covered in the classes *low and very low chloride penetration*. Resistivity values contained in “m” range between 15 and 0% will be represented by a *negligible chloride penetration* class.

Applying the minor limit of the ranges (75%, 55%, 35%, and 15%) on Eq. (2) the limit values of surface electrical resistivity obtained were 9, 17, 41 and 220 kΩ·cm, being this the values presented in classes in Table 4. As can be seen, the values proposed are close to values presented in Table 1 by Refs. [25,26,28]. In this perspective, comparing the new proposed values (Table 4) with the values described by Refs. [25,26] the class “*very high chloride penetration*” was inserted in the text when surface electrical resistivity is lower than 5 kΩ·cm, whereas, the range of surface electrical resistivity for higher chloride penetration was defined between 5 and 9 kΩ·cm, refining the standards and literature parameters.

The proposed ranges of 9–17 kΩ·cm, 17–41 kΩ·cm, 41–220 kΩ·cm in Table 4 correspond to moderate, lower and very low chloride penetration respectively, showing that standards values describe by Refs. [25,26] are close to the values presented in this work. Thus, by the exposed, the proposed new parameters not only confirm the applicability of standards parameters for field applications, but present a contribution refining the range values and the correlation between chloride penetration and concrete electrical resistivity. In this sense, one of the main contributions of this work was in order to refine the standards parameters for better interpretations of the real chloride penetration in marine structures for service life studies by a nondestructive technique.

4. Conclusions

This paper presents a new proposal of values to correlate chloride penetration and surface electrical resistivity using chloride profiles of structures present in marine environment. Based on the results of this experimental investigation, the following conclusions are drawn:

1. Carbonation assays show that in the studied environment the reinforcement corrosion was due to the action of chlorides present in different marine aggressive zones, once carbonation fronts observed were limited to 3 mm depth. Pacometry assays shown that when structures were built, the same concrete cover thickness was applied for all the structures independently of the marine aggressive zone were it were built.
2. Surface electrical resistivity is a simple non destructive technique capable to be correlated with chloride penetration. It was observed that surface electrical resistivity and the sum of chlorides concentration in the chloride profiles presented an inversely proportional relationship. In other words, it was noted that low surface electrical resistivity values indicate higher chloride concentrations on chloride profiles. This behavior is justified due to the interconnected concrete pores network, since charge flow and chlorides mobility are easy when concrete present high volume of interconnected pores network.
3. Square root function is a suitable form to represent the relationship between the sum of chlorides concentration from the profile and the surface electrical resistivity, mainly if the chloride profiles present a nitid peak of maximum chloride concentration, where a R² igual to 0.95 was observed.
4. New limit values regarding the chlorides penetration and surface electrical resistivity were proposed e compared with standards parameters. The analysis obtained in this work were close to the standards values, however, new classes and new range values were inserted refining the standards currently parameters.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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