



Analysis of Different Parameters in the Electrical Resistivity Test of Concrete

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Abstract

Electrical resistivity is widely used to monitor the durability of concrete structures. However, the results obtained can be misinterpreted due to the effect of several parameters on the test. Therefore, the effect of six parameters on the electrical resistivity was investigated in this article. The studied parameters were (1) the thickness of the concrete cover; (2) the contact with the concrete mold; (3) the concrete aging; (4) the chloride presence; (5) the type of cure and exposure; and (6) the position of the equipment regarding the reinforcement direction. Tests were performed on aged non-reinforced concrete specimens (5 years old) and freshly casted specimens. The results showed that variation in the thickness of the reinforcement covers from 1.5 to 3.0 cm affects the electrical resistivity measurements, independently of the w/c ratio. The contact of the concreting mold with the specimen did not influence the values of electrical resistivity, independently of the w/c ratio. The effect of the chlorides incorporated into the mass of the concrete during casting is not significant on the electrical resistivity at 28 days. The electrical resistivity was 13.2% higher in specimens cured in a moist chamber, compared to curing in an uncontrolled external environment. The electrical resistivity was no longer influenced by the steel at a minimum parallel distance of 8.0 cm. Measurements performed perpendicular to the bar were not affected. These results are very important for a better interpretation of the results of this technique.

Keywords Electrical resistivity · Werner method · Reinforcement · Curing · Concrete age

1 Introduction

Reinforcement corrosion is a degradation process that can affect the service life of reinforced concrete structures. The electrical resistivity of concrete is an important parameter related to this electrochemical process. Therefore, electrical resistivity has been widely used to monitor the quality of concrete in real structures [1–3]. Some correlations

between the probability of corrosion and electrical resistivity are proposed by different studies and standards [4, 5]. This parameter has also been used to model the service life of concrete structures [6]. The electrical resistivity of concrete can be obtained by performing other techniques, such as electrochemical impedance spectroscopy [7], or even can be used as a complementary decision tool for other tests, such as ultrasonic pulse velocity [8]. There are several possible applications for the electrical resistivity data of concrete.

Shahmansouri et al. [9] verified the hypothesis of estimating the electrical resistivity of eco-friendly concrete. The predicted values of the random mix designs were compared with experimental results for validating the models used. The models showed values close to the experimental results. Mendes et al. [6] proposed a model to include electrical resistivity in the design of concrete mixtures. This methodology contributed to include resistivity data for a concrete mixture to reach a pre-established service life.

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The Werner method consists of using four contact electrodes spaced at equal distance and positioned on the concrete surface. The equipment applies an alternating current (I) between the external contacts and measures the potential difference (V) between the two internal contacts. The monitoring of the electrical resistivity of the concrete by the Werner method has some advantages when compared to the volumetric electrical resistivity testing. For example, the surface electrical resistivity can be performed in situ through an easier execution procedure, being non-destructive, and requiring simpler equipment [10].

However, some disadvantages are associated with the technique of surface electrical resistivity. The method is proposed for a semi-infinite medium. Thus, a correction factor is necessary for the evaluation of small specimens. According to Gowers and Millard [11], this factor is necessary for specimens with dimensions less than 20 cm, considering equipment with spacing between electrodes of 5 cm. The Spanish UNE 83988-2 [10] standard provides some correction factors for sample sizes usually applied in a laboratory (for example, cylindrical samples of 10 cm diameter and 20 cm length). Another disadvantage of the technique is associated with its high sensitivity to different parameters. For example, maintaining the standardization of concrete moisture is very important to enable comparisons between studies. Therefore, measurements should be carried out on the concrete in saturated surface-dry (SSD) condition, whenever possible [12]. However, this condition is difficult to achieve in practical applications.

In addition, the electrical resistivity test may not be appropriate for evaluating concrete penetrability in concretes with sugarcane bagasse ash and ground glass. The conductive solution of these materials can result in electrical-based penetrability classifications different from those classifications from physical/non-electrical testing [13]. Also, the substitution of natural aggregates with Reused Concrete Aggregates (RCA) resulted in a considerable variation in the electrical resistivity of self-consolidating concretes [14].

Duran-Herrera et al. [15] showed that the electrical resistivity measurements increase with the replacement of Type I Portland cement by fly ash. However, the fly ash substitution by limestone filler can reduce the electrical resistivity. According to Coppio et al. [16], concretes with waste foundry sand as aggregate may have a reduction in electrical resistivity compared to a reference concrete (natural aggregate).

Therefore, several factors can affect the electrical resistivity measurements. Some of these factors are the water to cement (w/c) ratio [17], aggregates [14, 16, 18, 19], presence of ions in the concrete [20–23], porosity [6, 13, 24], compressive strength, carbonation, temperature and age of the concrete [25, 26], chemical

admixtures [27, 28], mineral additions [15, 29], and specimen dimensions [25, 30]. Curing conditions and the reinforcement diameter also have an important effect on resistivity [23, 31]. Among these factors, w/c ratio, moisture, reinforcement presence, hydration degree, and cement type are the parameters that have the greatest influence [32].

Therefore, although it is an extremely important test to monitor the durability of concrete, the results of electrical resistivity are often misinterpreted due to a number of factors that interfere with the measurements. This impairs a more accurate diagnosis of the safety conditions of concrete structures. The purpose of this article is to study the variation of the electrical resistivity of concrete specimens under different conditions. The effects evaluated were (1) the thickness of the concrete cover; (2) the contact with the concrete mold; (3) the concrete aging; (4) the chloride presence; (5) the type of cure and exposure; and (9) the position of the equipment regarding the reinforcement direction.

Unlike most studies related to the electrical resistivity of cement-based materials [6, 18, 27, 28], this article investigates the effect of the position of the reinforcement on resistivity in aged concrete specimens (5 years old). Most studies are performed on specimens after up to 28 days of cure. This makes it difficult to isolate the effect of the reinforcement, since hydration reactions still occur at this age and interfere with the resistivity measurements [33].

In addition, many studies are concentrated on cement pastes or mortar [15, 17, 33–35]. Although these studies are important, the methodology applied to cement paste or mortar often aims to simulate an existing condition in reinforced concrete structures. However, the porous structure of the cement paste or mortar is known to be different from that observed in concretes, mostly because of the porosity in the interfacial transition zone (ITZ). This makes it difficult to extrapolate the results of these studies into concrete structures.

Another important innovation of this article is the monitoring of the electrical resistivity of concrete up to 209 days to evaluate the effect of concrete aging. According to Medeiros-Junior et al. [29], the electrical resistivity data over time can be modified due to some long-term phenomena, such as carbonation. The authors found that the effect of the w/c ratio on the resistivity of concrete can be reversed over time. At an early age, the increase in the w/c ratio tends to reduce the concrete electrical resistivity. However, as concrete with a higher w/c ratio tends to carbonate faster, Medeiros-Junior et al. [29] observed that after 500 days, the concrete with a w/c ratio of 0.60 showed higher electrical resistivity than concrete with w/c ratio of 0.40. According to Mosavinejad et al. [33], the effect of silica fume in reducing the

permeability of cement-based materials was supported by the trend of increasing electrical resistivity after two years of monitoring.

Most studies on resistivity are concentrated on concrete without reinforcement [6, 17–19, 23, 27]. However, most of the civil buildings are made of reinforced concrete. This makes it difficult to extrapolate the results of the literature to decision making in the field. Thus, this article also intends to contribute to this theme by evaluating the effect of three thicknesses of the concrete cover and the position of the equipment regarding the reinforcement direction. Some current studies have made efforts to model this effect. Lim et al. [36] proposed a mathematical model for the quantitative estimation of geometric effects of nearby rebar in electrical resistivity measurement. Lim et al. [37] showed a model for resistivity estimation along the direction of electrode array above rebar.

In addition, this article carried out an extensive experimental campaign to evaluate six different parameters in the electrical resistivity measurements of concrete. Although the entry of chlorides in resistivity has already been extensively studied in the literature, this article evaluated the effect of chlorides added during concrete casting. In most of the articles [38–40], the effect of chloride from the external environment is evaluated, differently from this research. The intention of evaluating the chlorides added during concrete casting is to simulate situations where this ion is found in the concrete raw material, such as aggregates or contaminated water.

The effect of the concrete face is also associated with practical situations. It is often not possible to choose the face of a beam or slab to monitor the electrical resistivity of concrete in real structures. Thus, this article aims to investigate whether contact with the mold during concrete casting can interfere with electrical resistivity measurement.

2 Experimental Program

Electrical resistivity measurements were performed by the Werner method on the surface of several reinforced and non-reinforced specimens of different characteristics. Concrete specimens under different conditions were studied: aged specimens (5 years old) with cement hydration supposedly stabilized; and specimens freshly casted in which it was possible to monitor the influence of concrete aging on electrical resistivity.

2.1 Materials

2.1.1 Aged Specimens: Effect of the Thickness of the Concrete Cover and the Contact with the Concrete Mold

Brazilian commercial CP IIE cement was used (Table 1). This cement has approximately 34% blast furnace slag in its composition. Concrete specimens with cement content of 400 kg/m³ (*w/c* ratio = 0.45) and 200 kg/m³ (*w/c* ratio = 0.65) were studied. The choice of two *w/c* ratios was made to contribute to the applicability of the study. However, the effect of the *w/c* ratio on electrical resistivity is not one of the six parameters selected for this article since this effect is already well known and discussed in the literature [6, 13, 17, 24]. The fine aggregate was quartz sand and the coarse aggregate was gravel with a maximum dimension of 12.5 mm. The aggregates (fine and coarse) and the steel (reinforcement) used met the conditions of the ASTM C33 and ASTM A400 standards, respectively. All specimens were demolded after 48 h from casting and wet curing was applied for 28 days. These specimens were kept in a laboratory environment for 5 years and were not exposed to the external environment.

All aged specimens (5-years old) were prismatic with dimensions of 15.0 × 15.0 × 30.0 cm. Both reinforced and non-reinforced specimens were investigated and identified according to Table 2. The reinforced specimens showed differences in the concrete cover as shown in the scheme of Fig. 1. The following analyses were made in aged specimens: the thickness of the concrete covers (1.5, 2.0, and 3.0 cm) with different *w/c* ratios; and the effect of contact with the concreting mold (faces with and without

Table 1 Characteristics of the Portland cements

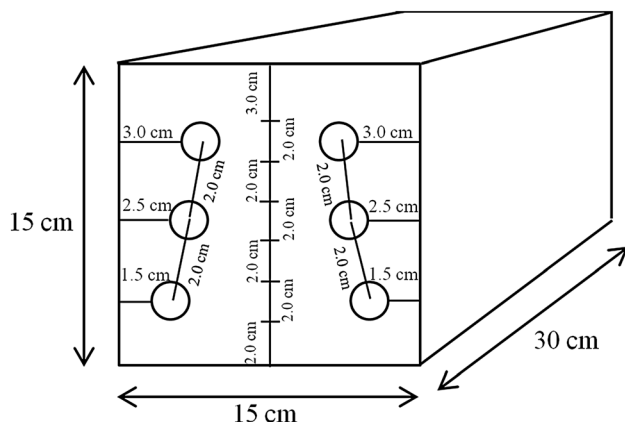
Properties	CP II-E	CP III RS
MgO (%) content ^a	6.5	–
SO ₃ (%) content ^a	4.0	4.0
Loss on ignition (%) ^a	6.5	4.5
Insoluble residue (%) ^a	2.5	1.5
#200 (75 μm) (%) ^a	12.0	8.0
Initial setting time (h: min) ^b	1:00	1:00
Final setting time (h: min) ^a	10:00	12:00
Expansibility (mm) ^a	5.0	5.0
Compressive strength—3 days (MPa) ^b	10.0	12.0
Compressive strength—7 days (MPa) ^b	20.0	23.0
Compressive strength—28 days (MPa) ^b	32.0	40.0

^aMaximum value

^bMinimum value

Table 2 Identification of aged concrete specimens

Code	Description
AR0.45	Aged reinforced (AR) concrete specimens ($w/c = 0.45$)
AR0.65	Aged reinforced (AR) concrete specimens ($w/c = 0.65$)
ANR0.45	Aged non-reinforced (ANR) concrete specimens ($w/c = 0.45$)
ANR0.65	Aged non-reinforced (ANR) concrete specimens ($w/c = 0.65$)

**Fig. 1** Scheme of the positioning of the reinforcing bars and variation of the cover thicknesses (1.5 cm, 2.0 cm, and 3.0 cm) of the aged reinforced test specimens

contact with the mold). Five specimens were molded for each analysis.

Specimens ANR0.45 and ANR0.65 were used for the analysis of the contact of the specimen faces with the mold on the electrical resistivity. Four faces were tested: the upper one that has not been in contact with the mold during casting and the three faces which have been in contact with the concrete mold for the first 48 h before demolding.

The face of the concrete specimen without contact with the mold (upper face) is naturally not smooth compared to the side faces. Therefore, the finishing of the specimens was carried out very carefully at the moment of their casting, with the use of tools (metal lab rulers, for example) that allowed the surface to be smoothed, to obtain a face with the least possible roughness. The electrodes of the resistivity equipment had foam at their ends, which facilitated the least interference of the face roughness in the Wenner probe.

2.1.2 Non-reinforced New Specimens: Effect of Concrete Aging, Chloride Presence and the Type of Cure and Exposure

Concerning the non-reinforced new specimens (freshly casted), Brazilian commercial CP III-RS cement was used (Table 1). This cement has approximately 60% blast

furnace slag in its composition. The w/c ratio was 0.54 (except for FNR-S specimens, $w/c = 0.60$). The cement content was $355 \pm 5 \text{ kg/m}^3$. The same method of casting and curing mentioned before was performed. After 48 h of casting, the specimens were demolded and subjected to different curing and exposure conditions (Table 3). Cubic specimens of $20.0 \times 20.0 \times 20.0 \text{ cm}$ dimension were used. Four specimens were molded for each analysis.

The following analyses were performed: effect of concrete aging (FNR-S); effect of the presence of chloride ions in the concrete (FNR-Cl and FNR-WC); and effect of the type of cure and exposure conditions (FNR-WC and FNR-EE). The values of electrical resistivity of FNR-S specimens were monitored until the age of 209 days to follow the aging effect of concrete on electrical resistivity. Sodium chloride (3% by mass of cement) was added during concrete casting in FNR-Cl specimens to analyze the effect of the presence of chloride. Although the workability of concrete mixtures can be reduced when sodium chloride is added, all mixtures carried out in this article showed a slump within a $75 \pm 10 \text{ mm}$ range.

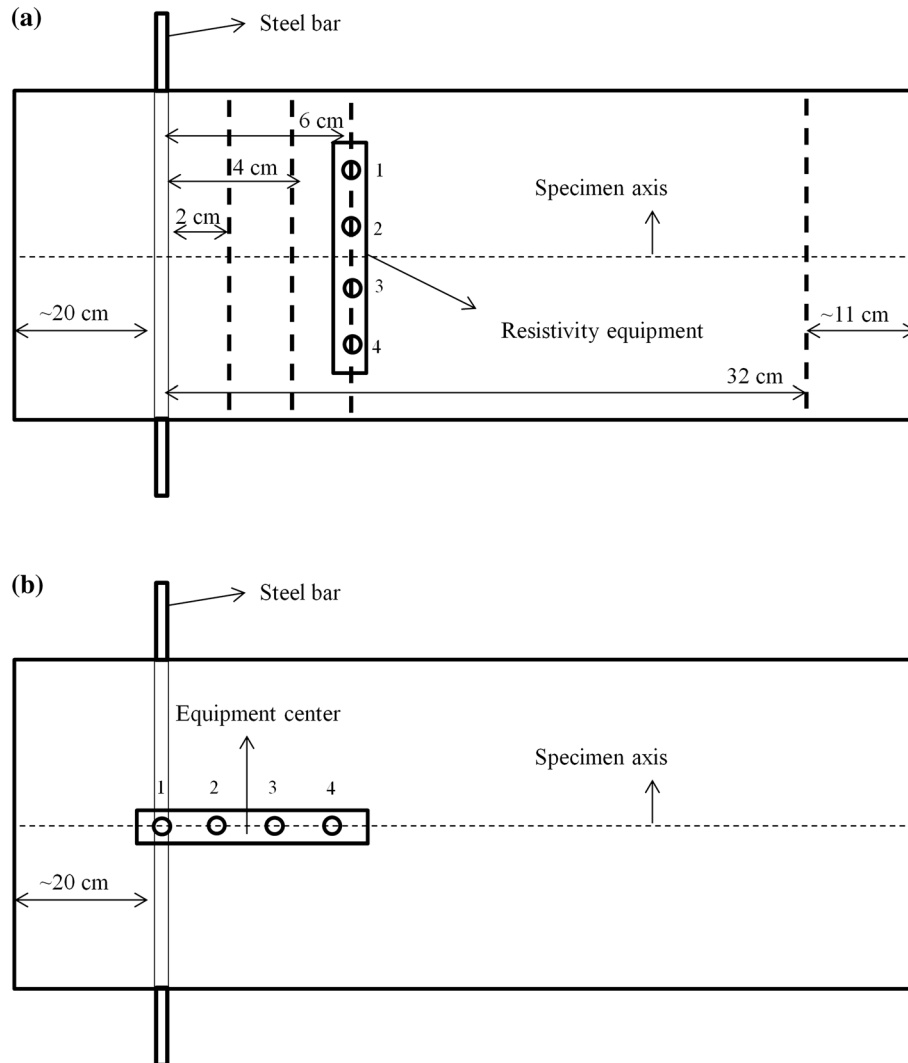
2.1.3 Reinforced New Specimens: Effect of the Position of the Equipment Regarding the Reinforcement

Specimens with $24.0 \times 24.0 \times 65.0 \text{ cm}$ dimensions were used to analyze the effect of the position of the equipment regarding the reinforcement on the electrical resistivity measurements. The concrete cover was 2.0 cm. The specimen (FR) had a single corrugated steel bar (2.0 cm in diameter) positioned perpendicular to the specimen axis (Fig. 2). Three specimens were molded for this analysis.

Brazilian commercial CP III-RS cement was used (Table 1). The w/c ratio and the cement content were 0.54 and 363 kg/m^3 , respectively. CA-50 steel bars were used following the characteristics of the ASTM A400 standard. The specimens were cast and kept in a laboratory environment for 28 days. After the casting, the surfaces of the specimens were kept constantly wet. Electrical resistivity measurements were performed over and parallel to the reinforcing bar. Measurements in parallel were performed every 2 cm until a total distance of 32 cm from the bar (Fig. 2a). In addition, some measurements were performed

Table 3 Identification of new non-reinforced concrete specimens

Code	Description	Curing time (days)
FNR-CI	Freshly casted non-reinforced (FNR) with chlorides: wet chamber cure	28
FNR-WC	Freshly casted non-reinforced (FNR): wet chamber cure	28
FNR-S	Freshly casted non-reinforced (FNR): submerged cure in a water tank	209
FNR-EE	Freshly casted non-reinforced (FNR): curing in an external environment (without control)	28

**Fig. 2** Scheme of the positioning of the reinforcing bars and the resistivity equipment: **a** parallel measures; **b** perpendicular measures

perpendicular to the reinforcement bar, varying the outer probe of the equipment (positions 1–4, Fig. 2b).

2.2 Methods: Electrical Resistivity Measurements

Electrical resistivity measurements were conducted based on the UNE 83988-2 [10] standard. The equipment used contains four equidistant electrodes with spacing equal to

50 mm (Fig. 3). The test was always applied with the wet concrete surface. The specimens were moistened with a spray bottle. Water was sprinkled to keep the entire surface moist, but without the presence of accumulated water. Therefore, the specimens were moistened one by one, immediately before the electrical resistivity test.

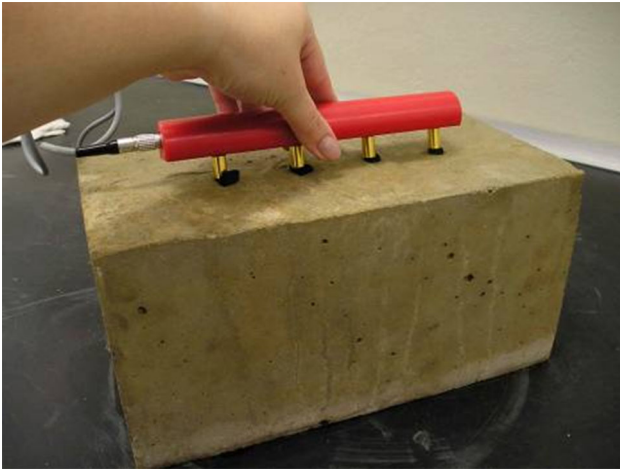


Fig. 3 Electrical resistivity test being performed

3 Results and Discussions

3.1 Thickness of the Concrete Cover and the Effect of Contact with the Concrete Mold

Cover thicknesses of 1.5 cm, 2.0 cm, and 3.0 cm were evaluated. Reference values and range (reference values $\pm 20\%$) for electrical resistivity were obtained by the non-reinforced ANR0.45 and ANR0.65 specimens (see Table 2). The range was determined based on the data presented by RILEM TC 154 [4], which define as admissible a variation of 20% in the values obtained with the electrical resistivity tests. Figures 4 and 5 show the effect of the thickness of the concrete cover on the electrical resistivity of concretes with w/c ratios of 0.45 and 0.65, respectively. Figures 4 and 5 also show the ranges of the

probability of corrosion of the reinforcement, as suggested by Balestra et al. [5].

The analysis of variance (ANOVA) and Tukey test indicated that the variation in the thickness of the reinforcement covers from 1.5 cm or 2.0 cm to 3.0 cm affects the results of electrical resistivity (Tables 4 and 5), independently of the w/c ratio. However, the electrical resistivity of specimens with concrete covers of 1.5 cm and 2.0 cm is statistically not significant. This means that these two measures can be considered as equal. The R^2 value provided by the exponential trend line of the graphs indicates that the regression model adopted explains 78% and 94% of the data variability. Considering that variations of 20% are acceptable [4], there was a good adjustment of the empirical model to the data in both cases.

Regarding the corrosion probability criterion proposed by Balestra et al. [5], values obtained in non-reinforced specimens (ANR0.45 and ANR0.65) are in the moderate probability range of corrosion. However, the values registered for the coverings of 1.5 cm and 2.0 cm indicated very high corrosion probability, independently of the w/c ratio. The values obtained for the covering of 3.0 cm indicated a moderate probability of corrosion. These values showed that the variation of the cover thickness affects the measurements, which can lead to erroneous conclusions on the real situation of a concrete structure or element, in agreement with other studies [11]. Electrical resistivity measurements over reinforcing bars result in (false) low values and should be avoided whenever possible.

Figure 6 shows the effect of the face in contact with the concrete mold on electrical resistivity.

Despite an apparent difference between values, when applying the analysis of variance to the data (5% of significance), the contact of the concreting mold with the specimen did not significantly influence the values of

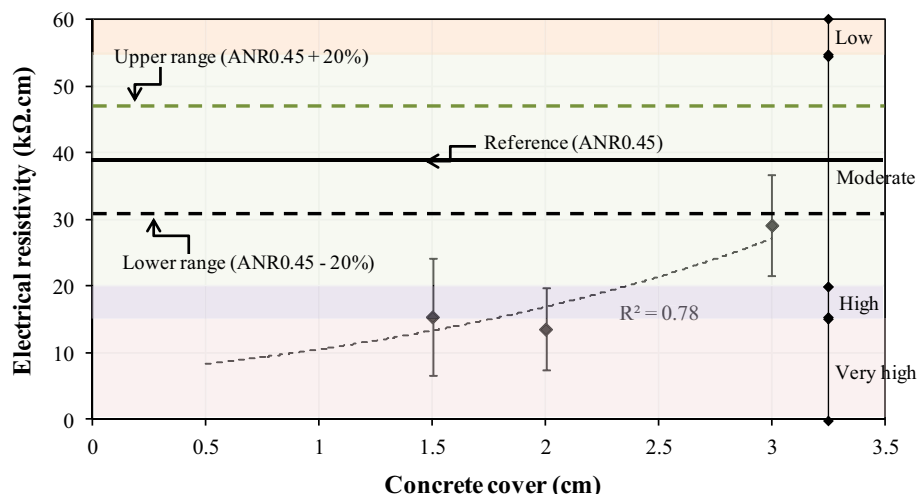


Fig. 4 Effect of the thickness of the concrete cover on the electrical resistivity of concrete with a w/b ratio of 0.45

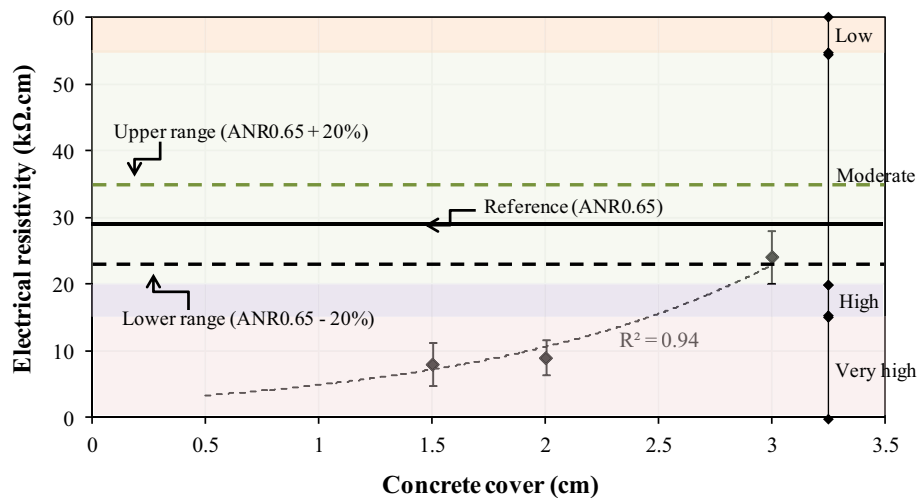


Fig. 5 Effect of the thickness of the concrete cover on the electrical resistivity of concrete with a *w/b* ratio of 0.65

Table 4 Statistical analysis (Tukey test) of the effect of the thickness of the concrete cover on the electrical resistivity—*w/b* ratio = 0.45

Interaction between groups	Mean difference	<i>p</i> value	Status
1.5 vs 2.0	1.833	0.827	Statistically not significant
1.5 vs 3.0	− 13.750	0.000	Statistically significant
2.0 vs 3.0	− 15.583	0.000	Statistically significant
Total	1293.753		

The smaller the *p* value, the stronger is the evidence that the null hypothesis should be rejected. A *p* value equal or less than 0.05 is statistically significant, as there is a ≤ 5% probability that the results are random

Table 5 Statistical analysis (Tukey test) of the effect of the thickness of the concrete cover on the electrical resistivity—*w/b* ratio = 0.65

Interaction between groups	Mean difference	<i>p</i> value	Status
1.5 vs 2.0	− 0.967	0.756	Statistically not significant
1.5 vs 3.0	− 16.117	0.000	Statistically significant
2.0 vs 3.0	− 15.150	0.000	Statistically significant
Total	1293.753		

The smaller the *p* value, the stronger the evidence that the null hypothesis should be rejected. A *p* value equal or less than 0.05 is statistically significant, as there is a ≤ 5% probability that the results are random

electrical resistivity, independently of the *w/c* ratio. Therefore, in the case of the effect of the concreting mold on electrical resistivity, the small difference in Fig. 6 was proven to be insignificant (casual) by ANOVA test (Tables 6 and 7). Thus, the value of electrical resistivity is independent of which face of the concrete specimen the measurement is performed.

3.2 Concrete Aging

This analysis sought to define the period in days from which variations in electrical resistivity of concrete were

less expressive. Indirectly, the influence of the hydration of the CP III-RS cement on the concrete electrical resistivity was analyzed through the progress of this property. Figure 7 shows the electrical resistivity of FNR-S specimens (non-reinforced specimens under submerged curing) measured up to the age of 209 days.

According to the analysis of variance applied to the presented data, the age of the concrete specimens increases the values of electrical resistivity, considering 95% of the level of confidence. The values of electrical resistivity tend to become constant according to the stabilization of the cement hydration. Regarding the FNR-S specimens, it was

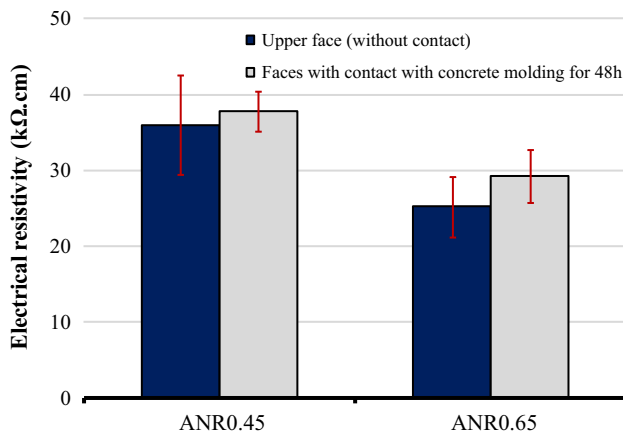


Fig. 6 Electrical resistivity values in ANR0.45 and ANR0.65 specimens, measured on faces with and without contact with the concreting mold

possible to distinguish the tendency of stabilization of the values for cement CP III-RS after 120 days. The stabilization of the electrical resistivity was estimated at around 50 kΩ.cm for this type of cement. According to the regression model, this value is reached at 275 days. When the value of the electrical resistivity of a concrete (stabilization tendency) is estimated, it can be used in future analyses of the conditions of durability or service life prediction [6].

3.3 Presence of Chlorides in Concrete

The electrical resistivity of FNR-Cl and FNR-WC specimens (both in the same curing condition) were 27.3 ± 0.9

kΩ.cm and 27.5 ± 1.3 kΩ.cm, respectively, at 28 days. The analysis of variance (ANOVA) with 95% confidence confirmed the inexistence of the effect of the addition of chlorides on the electrical resistivity.

The presence of chlorides in the concrete and its influence on the electrical resistivity is somewhat contradictory and that, in itself, is the subject of extensive research. Some authors have found reductions in resistivity with the increase of chloride ions in the concrete pores [12, 23, 25, 38–40]. Thus, the results found in this article are contradictory to some outcomes from the literature. However, one important point should be highlighted. In this research, the chloride was incorporated into the mass of the concrete during casting, while the majority of the studies analyzed the diffusion of chlorides from an external source. Therefore, further investigation is advised in order to compare and validate the obtained results, being encouraged to perform analyzes varying the percentage of chlorides, test ages, and cement types.

3.4 Effect of Type of Cure and Exposure Conditions

The monitoring of the electrical resistivity of the FNR-EE specimens (aging in an external environment without controlled curing) and FNR-WC (curing in a moist chamber) provided the following values at 28 days: 24.3 ± 1.5 kΩ.cm and 27.5 ± 1.3 kΩ.cm, respectively. According to the data, the average electrical resistivity in FNR-WC specimens was 13.2% greater than the average value obtained from FNR-EE specimens. The difference in values obtained for the different conditions of cure and

Table 6 Statistical analysis (ANOVA) of the effect of the concreting mold on electrical resistivity— w/b ratio = 0.45

Variation source	Square sums	Degrees of freedom	Square means	p value	Status
Between groups	8.100	1	8.100	0.606	Statistically not significant
Within groups	224.360	8	28.045	–	–
Total	232.460	9	–	–	–

The smaller the p value, the stronger the evidence that the null hypothesis should be rejected. A p value equal or less than 0.05 is statistically significant, as there is a $\leq 5\%$ probability that the results are random

Table 7 Statistical analysis (ANOVA) of the effect of the concreting mold on electrical resistivity— w/b ratio = 0.65

Variation source	Square sums	Degrees of freedom	Square means	p value	Status
Between groups	40.401	1	40.401	0.127	Statistically not significant
Within GROUPS	111.428	8	13.929	–	–
Total	151.829	9	–	–	–

The smaller the p value, the stronger is the evidence that the null hypothesis should be rejected. A p value equal or less than 0.05 is statistically significant, as there is a $\leq 5\%$ probability that the results are random

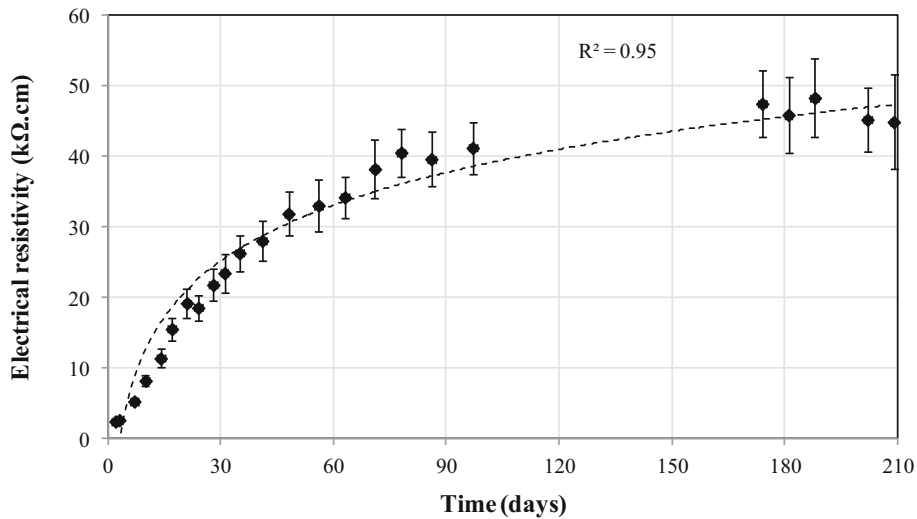


Fig. 7 Evolution of the electrical resistivity in FNR-S specimens

exposure is justified since the cement hydration under constant moistening (moist chamber) progresses easily when compared to exposure to the external environment. In the latter condition, the material is exposed to bad weather, and there are environmental variations (humidity, temperature, winds). This result is important, as it shows that the moisture conditions of the concrete must always be standardized in-field measurements with real structures for a better interpretation of the result.

3.5 Effect of the Position of the Equipment Regarding the Reinforcement Direction

Specimens with a single reinforce bar of diameter 2.0 cm and 2.0 cm concrete cover positioned perpendicular to the axis of the specimen (FR) were used. Figure 8 presents the

electrical resistivity results at 28 days measured over (0 cm) and parallel to the reinforcing bar (from 2 to 32 cm of distance).

The distance to the steel bar inside the concrete influences the electrical resistivity measurements, according to the ANOVA test. The analysis of variance was applied once again in order to detect which distance of the reinforcing bar influences the concrete electrical resistivity. Concerning specimens with single rebar of diameter 2.0 cm and 2.0 cm concrete cover, readings made by positioning the Wenner probe parallel to the reinforcement were no longer influenced by the conductivity of the steel at a minimum distance of 8.0 cm. All measurements taken at lower distances were affected by the conductivity of the steel. Thus, the obtained data allows recommending the

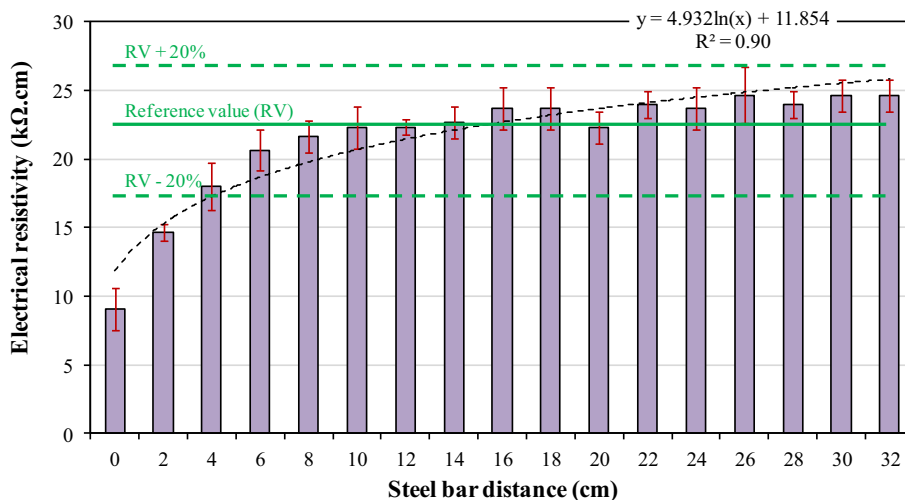


Fig. 8 Electrical resistivity of FR specimens at 28 days—parallel to the reinforcing bar

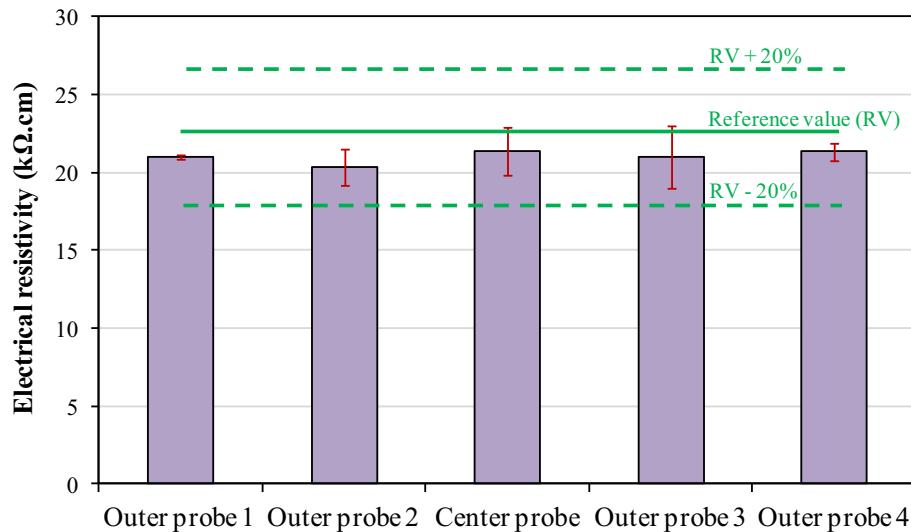


Fig. 9 Electrical resistivity of FR specimens at 28 days—perpendicular to the reinforcing bar

minimum distance of 8.0 cm parallel to the steel bar to avoid its influence on the resistivity measurement.

Figure 9 shows the electrical resistivity measurements perpendicular to the reinforcing bar of FR specimens.

The analysis of variance showed that measures of electrical resistivity performed perpendicular to a steel bar were not affected by the conductivity of the reinforcement. Thus, resistivity tests performed perpendicularly to the rebar do not present variations that disturb its results in the conditions tested in this article.

4 Conclusions

This article observed the effect of six parameters on the electrical resistivity measurements. The studied parameters were (1) the thickness of the concrete cover; (2) the contact with the concrete mold; (3) the concrete aging; (4) the chloride presence; (5) the type of cure and exposure; and (6) the position of the equipment regarding the reinforcement direction. Aged non-reinforced concrete specimens (5 years old) and freshly casted specimens were tested. Based on the results obtained, it was possible to draw the following conclusions:

(1) The electrical resistivity values measured for the coverings of 1.5 cm and 2.0 cm indicated very high corrosion probability, independently of the w/c ratio. However, the electrical resistivity values indicated a moderate probability of corrosion for the covering of 3.0 cm. Therefore, the variation of the concrete cover thickness can affect the measurements and must be taken into account when monitoring a concrete structure.

- (2) The electrical resistivity is independent of the face of the concrete element.
- (3) The variability of electrical resistivity is a function of the time (hydration of the cement). It was possible to distinguish the tendency of stabilization of the values for concrete with blast furnace slag Portland cement after 120 days.
- (4) There was no significant influence on the electrical resistivity coming from the addition of 3% of chlorides to the concrete mass for measurements at 28 days. The results are contradictory with some outcomes from the literature and deserve to be better studied.
- (5) The average electrical resistivity of concrete curing in a moist chamber was greater than the value obtained from specimens aging in an external environment without controlled curing.
- (6) Electrical resistivity measured parallel to the reinforcement was no longer influenced by the conductivity of the steel at a minimum distance of 8.0 cm. Also, the electrical resistivity performed perpendicular to a steel bar was not affected by the conductivity of the reinforcement. This is valid for the conditions adopted in this article (concrete specimens with single rebar with 2.0 cm of diameter and 2.0 cm of concrete cover).
- (7) It is recommended that all of these conclusions be taken into account when carrying out electrical resistivity measurements on real concrete structures. This will make it possible to issue a more accurate diagnosis of the structure's durability condition.

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