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Resistivity thresholds to evaluate durability of concrete with waterproofing agents and different water/cement ratios

A. Guzmán[1]*
*Contact author: mguzman@frm.utn.edu.ar
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ABSTRACT

In the present work it is evaluated how the variation of the water/cement ratio influences the electrical resistivity of the concrete; the type of cement selected (CPP and CPF); and the incorporation of a water repellent. Cylindrical specimens were made on which the resistivity was evaluated using the Wenner probe method. Comparing the results obtained with the threshold values indicated in the literature, it is possible to understand the importance of this degradation mechanism that implies limiting the maximum w/c ratio to 0.45. On the other hand, the CPP cement turned out to be the one with the best performance, giving rise to higher resistivity results, while the incorporation of the water repellent had a null or counterproductive effect on said parameter.
Keywords: durability; corrosion; Wenner probe; electrical resistivity.

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[1] CeReDeTeC (Centro Regional de Desarrollos Tecnológicos para la Construcción, Sismología y la Ingeniería Sísmica), Facultad Regional Mendoza, Universidad Tecnológica Nacional, Mendoza Argentina.

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Umbrales de resistividad para evaluar durabilidad del hormigón con hidrofugantes y diferentes relaciones agua/cemento

RESUMEN

En el presente trabajo se evalúa cómo influye en la resistividad eléctrica del hormigón la variación de la relación agua/cemento; el tipo de cemento seleccionado (CPP y CPF); y la incorporación de un hidrófugo. Se confeccionaron probetas cilíndricas sobre las que fue evaluada la resistividad mediante el método de la sonda de Wenner. Comparando los resultados obtenidos con los valores umbrales indicados en la literatura, se permite entender la importancia que frente a este mecanismo de degradación implica limitar a 0.45 la máxima relación a/c. Por otra parte, el cemento CPP resultó ser el de mejor desempeño, dando lugar a mayores resultados de resistividad, mientras que la incorporación del hidrófugo tuvo un efecto de nulo a contraproducente en dicho parámetro.

Palabras clave: durabilidad; corrosión; sonda Wenner; resistividad eléctrica.

Limites de resistividade para avaliar a durabilidade do concreto com impermeabilizante de massa e diferentes relações água/cimento

RESUMO

No presente trabalho avalia-se como a variação da relação água/cimento influencia na resistividade elétrica do concreto; o tipo de cimento selecionado (CPP e CPF); e a incorporação de um impermeabilizante à massa de concreto. Corpos de prova cilíndricos foram feitos nos quais a resistividade foi avaliada usando o método da sonda de Wenner. Comparando os resultados obtidos com os valores limites da literatura, foi possível perceber a importância de limitar a relação água cimento em 0,45, para aumentar a resistividade do concreto acima de certos limites consagrados. Por outro lado, o cimento CPP (pozolânico) revelou-se o que apresentou melhor desempenho, originando resultados de resistividade mais elevados, enquanto a incorporação do impermeabilizante de massa teve um efeito nulo ou contraproducente neste parâmetro.

Palavras-chave: durabilidade; corrosão; Sonda de Wenner; resistividade elétrica.

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1. INTRODUCTION

Although reinforced concrete turns out to be a very durable material in most environments, the entry of chlorides, carbonation, or the leaching of calcium compounds can favor the corrosion of the reinforcements and thus, the degradation of the concrete. The corrosion of reinforcement is the result of the chemical transformation of the iron (Fe) that constitutes them, into hydrated ferric oxide or simply oxide (Fe2O3•H2O + 2H2O). This oxide has a volume of approximately 6 times that of the iron it replaces when it is not oxidized. This bulking up at the rebar/concrete interface is what leads to cracking and loss of the concrete covering, and to the brittle and flaking red/brown rust that occurs on the bars.
In this sense, concrete gives steel protection of a double nature: on the one hand, it is a physical barrier that separates it from the environment, and on the other, the liquid enclosed in the concrete pore solution is an electrolyte that can form a layer of protective oxide around the reinforcement, known as a passive film, with very adherent, compact and invisible characteristics (Irassar, 2001). This liquid in the pores, is constituted mainly by hydroxide ions (OH) which provide a high natural alkalinity to the concrete (pH ~ 12 to 13). The corrosion rate of the steel embedded in the concrete will depend, among other variables, on its electrical resistivity. Thus, concrete, like other materials, have properties that identify them, electrical resistivity being one of them.
This property is a measure of the greater or lesser possibility that an electric current generated by the flow of ions can be conducted, in our case, through the concrete. The fact that a reinforced concrete presents a low electrical resistivity, will threaten its durability, since a high corrosion rate may occur in the steel bar when it is active, that is, depassivated and with availability of moisture and oxygen.
In this regard and based on a study carried out in Argentina (Di Maio et al., 2009) on a total of 177 structures evaluated, it is indicated that the percentage of structures affected by corrosion processes of their reinforcement reaches approximately 16%. From an analysis of 1512 cases with different pathologies in southern Brazil (Dal Molin, 1988), it was determined that the incidence of reinforcement corrosion represents 40% of the total damage. The economic impact of corrosion on US highway bridges was evaluated (Koch et al., 2002). In this regard, the direct annual cost of the corrosion of highway bridges is estimated at US$ 8.3 billion, which consists of 3.8 billion for the annual cost to replace structurally deficient bridges in the next 10 years, and some 5.0 billion for maintenance. In the UK, the Department for Transport estimate of salt-induced corrosion damage is a total of £616.5 million on motorway bridges and trunk roads in England and Wales alone (Wallbank, 1989). These bridges represent around 10% of the total inventory of bridges in the country. Therefore, the final cost can be 10 times greater than that estimated by the Department of Transportation. The statistics for Europe, Asia Pacific and Australia are similar.
The above shows how the degradation problems of reinforced concrete structures associated with reinforcement corrosion turn out to be very significant, and compared to this, the high costs involved in repairing these affected structures.
Thus, a methodology for predicting the useful life of reinforced concrete structures through the use of corrosion indicators was opportunely proposed (D'Andrea, 2010). In this sense, it was found that electrical resistivity is the best valued corrosion indicator in terms of technique and application attributes. It is a property that is appropriately correlated with the compressive strength and the transport capacity of aggressive agents into the concrete.
On the other hand, the need to be able to quantify the durability of concrete has led to the search for a test that was capable of considering all the phases that involve it, from the manufacture of concrete to its curing and hardening. Electrical resistivity as the inverse of conductivity-diffusivity is a property of concrete that allows its so non-destructive control. Resistivity is an indicator of setting and mechanical resistance, the degree of saturation of the concrete and therefore the degree

of curing and the impermeability or resistance to the entry of aggressive substances. Therefore, it is a parameter that allows relating the microstructure with the durable behavior of concrete (Andrade and D'andrea, 2011).

Since the corrosion process of concrete reinforcement is partly controlled by ion transport through the microstructure of the concrete, the ability of a material to resist charge transfer will depend on its electrical resistivity. Therefore, a connection between the corrosion process of the steel and the electrical resistivity of the concrete is to be expected (Hornbostel et al., 2013).

For this reason, and given the importance that resistivity acquires in the durability of reinforced concrete against corrosive processes, it is that the current approaches to concrete performance design tend to seek to be able to use characteristic parameters associated with durability, thus allowing to obtain a target resistivity, and in this way, achieve an appropriate useful life in service of the concrete (Andrade, 2018).

The parameters that condition the resistivity, and with it the durability against corrosion of the reinforcements, have to do with the porosity of the concrete, with the chemical composition of the pore solution, and with the degree of saturation of these (Polder et al., 2000).

Regarding the measurement of electrical resistivity, various regulations contemplate carrying out tests on concrete (NBR 9204, 1985; UNE 83988-2, 2008), as well as various international organizations related to the study of construction materials (RILEM TC-154-EMC, 2000; DURAR, 2008). Particularly with regard to the measurement method known as the four-prong (Wenner probe), this turns out to be a non-destructive test and simple to carry out.

As it has been pointed out, the electrical resistivity is a parameter that conditions the speed with which the corrosive process propagates in the embedded reinforcements. But in turn, the resistivity that concrete can develop depends on certain characteristics, such as the materials used, their proportions, and the placement, compaction, and curing techniques. Therefore, in the present investigation it is evaluated how particular aspects related to materials and design influence the electrical resistivity of concrete, such as: i) the variation of the w/c ratio (0.5, 0.6, 0.7 and 0.8); ii) the type of cement selected (pozzolanic and fillerized) and iii) the incorporation of an additive (water-repellent).

The different combinations between the parameters selected for the elaboration of the study concretes, gave rise to the realization of 16 pastonadas of which cylindrical specimens (100x200 mm) were obtained in a standardized manner according to Standard (IRAM 1534, 2004) and cured by immersion for 27 days. The resistivity measurements on each specimen were carried out using the CANIN device (Canin+, 2012) using the Wenner probe (4-point method).

2. ELECTRICAL RESISTIVITY AND MEASUREMENT BY MEANS OF THE WENNER PROBE

Once the passivity of the steel is destroyed, either by carbonation, leaching of calcium compounds or by penetration of the chloride ion, the speed at which the corrosion process develops is controlled by the electrical resistivity of the concrete, which is a function of directly from moisture content and oxygen availability. Resistivity is a measure of the ability of concrete to act as an electrolyte and, consequently, to be able to conduct corrosion currents.

Electrical resistivity is a property that a material presents to oppose the conduction of electrical current through it. Ohm's Law establishes that the intensity I of the electric current flowing through an electric conductor is directly proportional to the potential difference V applied, and inversely proportional to its resistance R, which can be expressed according to the following equation:

$$I = V / R \tag{1}$$

where I is the current intensity measured in amperes (A), V the potential difference measured in volts (V), and R the electrical resistance measured in ohms (Ω).
The degree of difficulty encountered by electrons in their displacements is called resistivity, and its value describes the behavior of a material against the passage of electric current, thus giving an idea of how good or bad a conductor it is. A high resistivity value indicates that the material is a poor conductor while a low value indicates that it is a good conductor. Electrical resistivity is defined as:

$$\rho_P = R * A / L \tag{2}$$

where ρp is the electrical resistivity measured in (Ω.m), A is the cross-sectional area of the material (m^2), L is the length (m) and E is the electrical potential measured in volts (V). Figure 1 presents a representative schematic of resistivity measurement.

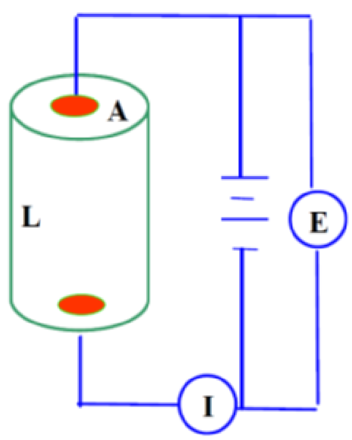

Figure 1. Representative scheme for the determination of electrical resistivity.

To measure the resistivity of existing structures, as well as in laboratory specimens, it is common to use the Wenner four-point probe as a technique (Polder et al., 2000) (Figure 2).

Figure 2: Wenner probe used. Measurement scheme.

On the surface to be measured, the electrodes are placed in line separated by a distance from each other (in this case a = 50 mm), an alternating current is applied through the extreme electrodes and the resulting potential drop is measured with the internal electrodes. Figure 2 shows the measurement scheme using the probe, with the measured Wenner resistivity being the one indicated in the following expression:

$$\rho_W = 2 * \pi * a * V / L \qquad (3)$$

3. EVALUATED CONCRETES

For the elaboration of the concretes, pozzolanic portland cement (CPP-40) and fillerized portland cement (CPF-40) were used, complying with the respective Standard (IRAM 50000, 2000). The aggregates used turned out to be of natural origin, with a nominal maximum size for the gravel of 19 mm. Regarding the water-repellent additive, an inorganic water-based waterproofing agent was used.

Sixteen types of concrete were evaluated, which were dosed by weight, with the ratio between the different components being the of one part of cement, two parts of fine aggregate, and three parts of cothe ofarse aggregate (1:2:3). In all cases, the weights of the materials were always the same, varying only the content of water and the water-repellent additive, the latter, in the study cases in which it was used.

The water-repellent additive was added to the mixing water in a dose that corresponded to removing 10% of the total mixing water and replacing this volume with that of the additive, thus resulting in a total volume of 9 parts of water plus 1 part of additive. Table 1 indicates the characteristics of the mixtures and the designation adopted for them.

Table 1. Designation of studio mixes. Material Ratio.

Designation	w/c ratio	Cement type	Additive type	Cement [c]	Water [w]	Sand [s]	Gravel [g]	Additive [H]
P-05	0.5	CPP-40 Pozzolanic (P)	-	1	0.50	2	3	-
P-06	0.6				0.60			-
P-07	0.7				0.70			-
P-08	0.8				0.80			-
P-05-H	0.5		waterproof (H)		0.45			0.05
P-06-H	0.6				0.54			0.06
P-07-H	0.7				0.63			0.07
P-08-H	0.8				0.72			0.08
F-05	0.5	CPF-40 Fillerized (F)	-		0.50			-
F-06	0.6				0.60			-
F-07	0.7				0.70			-
F-08	0.8				0.80			-
F-05-H	0.5		waterproof (H)		0.45			0.05
F-06-H	0.6				0.54			0.06
F-07-H	0.7				0.63			0.07
F-08-H	0.8				0.72			0.08

4. EXPERIMENTAL DEVELOPMENT

The measurement of electrical resistivity is sensitive to the moisture content of the concrete. In order to guarantee an adequate measurement and at the same time the same initial conditions for each study mixture, prior to the measurement, the test cylinders were left in water immersion for 72 hours, thus achieving a saturation of the same. Then the test cylinders were removed and superficially dried with a cloth, thus proceeding immediately to the respective measurement of electrical resistivity. Figure 3 shows the measurement procedure carried out on one of the test cylinders.

Figure 3: Resistivity measurement procedure. CANIN device. Wenner probe.

The electrical resistivity measurements were carried out on each of the groups of the study mixtures, which each consisted of three test cylinders. In each of these three measurements were taken on its surface, with a spacing of each other of approximately 120°. A first general measurement was carried out in all the test cylinders, and after 15 days of this, a second measurement was carried out with the same methodology as the first. Table 2 shows the average Wenner resistivity values (ρw) obtained in each measurement instance and for each cylinder.
On the other hand, and in order to achieve a reliable reading, the Wenner probe's foam rubber pads were constantly moistened, thus favoring good electrical contact between the four tips and the concrete surface. At the same time, a slight pressure of the probe was exerted against the surface of the test cylinder until the reading of the device was stable and with an indication of a "Current" field greater than 50%, which guaranteed the reliability of the measurement.
The resistivity value for each mixture corresponded to the average of the measurements obtained in each group, each of them and as indicated, consisting of three test cylinders. From the measurement carried out, the Wenner electrical resistivity (ρw) was obtained, but since the test cylinder was a finite medium, a shape factor (Ff) had to be considered (UNE 83988-2, 2008; Morris et al. al., 1996) which takes into account the dimensions of the cylinder and the separation between the tips of the probe.
From said shape factor, it was then possible to determine the electrical resistivity of the test cylinder (ρp) according to the following equation:

$$\rho_P = \rho_W * Ff \quad (4)$$

For the dimensions of the test cylinders and the Wenner probe used, said factor was found to be 0.377. Table 3 shows the resistivity averages obtained for each of the evaluated mixtures.

Table 2: Average electrical resistivities ρw in test cylinders of each mix.

Test cylinders	**ρw (kΩ.cm) 1st measurement**	**ρw (kΩ.cm) 2nd measurement**	**Test cylinders**	**ρw (kΩ.cm) 1st measurement**	**ρw (kΩ.cm) 2nd measurement**
P-05-1	28.0	31.0	F-05-1	19.0	18.0
P-05-2	25.0	27.0	F-05-2	22.0	20.0
P-05-3	26.0	27.0	F-05-3	18.0	18.0
P-06-1	22.0	22.0	F-06-1	15.0	15.0
P-06-2	22.0	22.0	F-06-2	14.0	17.0
P-06-3	21.0	23.0	F-06-3	12.0	15.0
P-07-1	15.0	17.0	F-07-1	11.0	11.0
P-07-2	17.0	20.0	F-07-2	13.0	14.0
P-07-3	16.0	19.0	F-07-3	12.0	12.0
P-08-1	11.0	18.0	F-08-1	10.0	11.0
P-08-2	12.0	18.0	F-08-2	11.0	11.0
P-08-3	13.0	17.0	F-08-3	10.0	11.0
P-05-1-H	20.0	25.0	F-05-1-H	20.0	19.0
P-05-2-H	20.0	23.0	F-05-2-H	19.0	18.0
P-05-3-H	22.0	25.0	F-05-3-H	19.0	20.0
P-06-1-H	19.0	18.0	F-06-1-H	16.0	17.0
P-06-2-H	19.0	17.0	F-06-2-H	16.0	15.0
P-06-3-H	18.0	18.0	F-06-3-H	16.0	17.0
P-07-1-H	16.0	17.0	F-07-1-H	11.0	13.0
P-07-2-H	17.0	17.0	F-07-2-H	10.0	13.0
P-07-3-H	17.0	17.0	F-07-3-H	11.0	13.0
P-08-1-H	12.0	16.0	F-08-1-H	8.0	9.0
P-08-2-H	11.0	15.0	F-08-2-H	9.0	9.0
P-08-3-H	11.0	15.0	F-08-3-H	8.0	10.0

From the results obtained, the dependence of the electrical resistivity with the w/c ratio, with the type of cement, and with the incorporation of the water-repellent additive was observed (Figure 4). In this regard, the mixtures with the best performance in terms of electrical resistivity values obtained were those made with portland pozzolanic cement and without the incorporation of the water-repellent additive (P-0x).

Table 3: Average electrical resistivities ρw and ρp for each mixture.

Designation	ρw (kΩ.cm)	ρp (kΩ.cm)
P-05	27.3	10.3
P-06	22.0	8.3
P-07	17.3	6.5
P-08	14.8	5.6
P-05-H	22.5	8.5
P-06-H	18.2	6.8
P-07-H	16.8	6.3
P-08-H	13.3	5.0
F-05	19.2	7.2
F-06	14.7	5.5
F-07	12.2	4.6
F-08	10.7	4.0
F-05-H	19.2	7.2
F-06-H	16.2	6.1
F-07-H	11.8	4.5
F-08-H	8.8	3.3

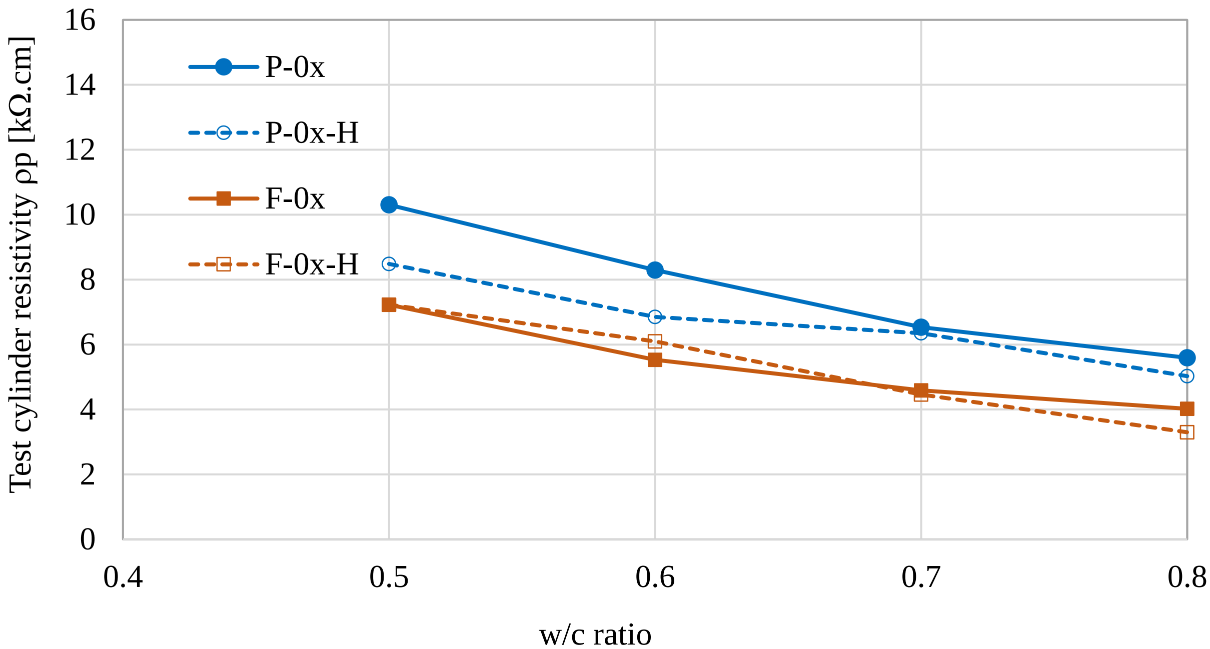

Figure 4: Electrical resistivities obtained for the different study mixtures.

Given the lack of regulations in the Argentine Republic that address the evaluation of electrical resistivity in concrete, the measurements obtained in this study were compared with threshold values obtained by Smith et al. (2004) based on various empirical tests carried out on concrete. Similar threshold values were reported by Cavalier and Vassie (1981), Hope et al. (1985), Broomfield and Millard (2002), as well as the instructions for use of the Proceq corrosion analyzer (Canin+, 2012).

These adopted threshold values are used to infer the probability of reinforcement corrosion, resulting in general that: i) If ρp > 12 kΩ.cm it is not probable that there is corrosion; ii) If 8 kΩ.cm < ρp < 12 kΩ.cm it is possible that there is corrosion; and iii) If ρp < 8 kΩ.cm it is very likely that there is corrosion.

It should be noted that in none of the study cases and for the w/c ratios considered was it possible to reach the area of low corrosion probability.

In this regard, and with the experimental results obtained in each mixture and graphed, a backward extrapolation was carried out (Figure 5), representing the aforementioned thresholds at the same time.

From what was graphed, it was possible to infer what turned out to be the best performing mixture (P-0x). On the other hand, it was also possible to establish what would be the maximum limit for the w/c ratio below which concretes with convenient levels of electrical resistivity would be obtained. On the other hand, it was also possible to establish what would be the maximum limit for the w/c ratio below which concrete with convenient levels of electrical resistivity would be obtained, and with it, low probability of occurrence of the corrosion phenomenon. This inferred upper limit for the w/c ratio and for the indicated mix was found to be approximately 0.45. The rest of the mixtures and for w/c ratios inferred between 0.40 and 0.45 from the indicated extrapolation, would present electrical resistivity levels that would correspond to an medium probability of occurrence of the corrosion phenomenon.

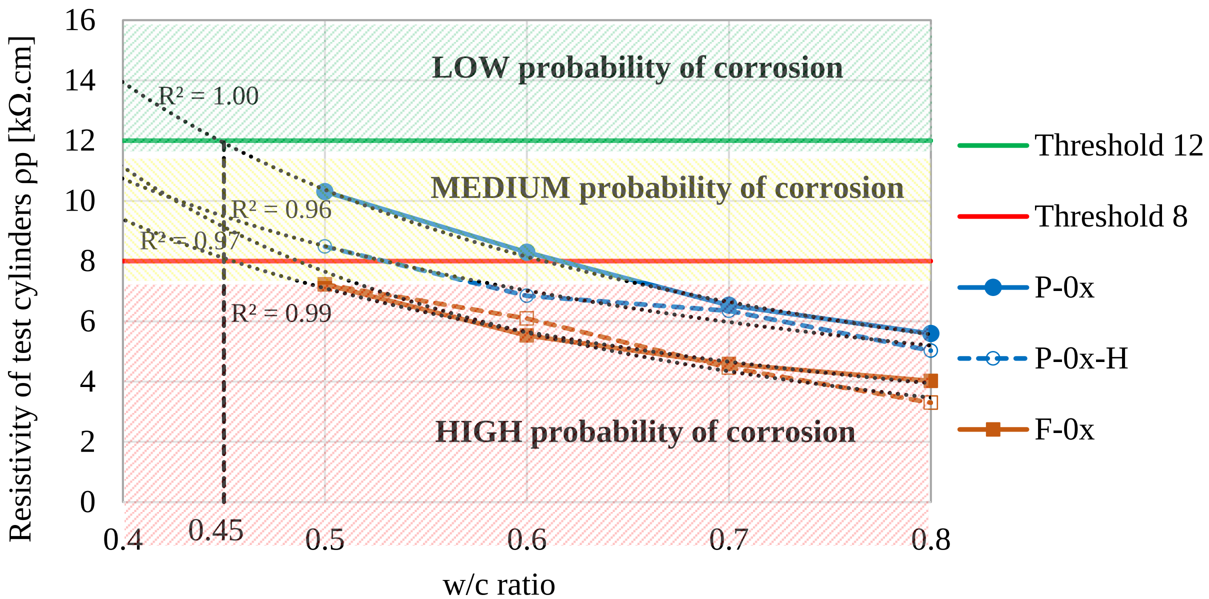

Figure 5: Resistivity thresholds (Smith et al., 2004).

Particularly for the case of the P-0x mixture, said inferred limit for the w/c ratio is in the order of the maximum values indicated by the Argentine Regulation of Concrete Structures (CIRSOC 201, 2005) in its Table 2.5, for the cases of reinforced and prestressed concrete. The w/c ratio is one of the durability requirements to be taken into account for the most severe exposure conditions that are highly conducive to the development of corrosion in reinforcements. In Table 4, which turns out to be an adaptation of the aforementioned Table 2.5, the different maximum w/c ratios are presented depending on the type of concrete and the class of environmental exposure. It should be noted that the exposure classes defined as A1, A2 and A3 correspond to the process of corrosion by carbonation; the CL, M1, M2 and M3 to the corrosion process by chlorides; C1 and C2 to freeze-thaw attack; and Q1, Q2 and Q3 to a chemical attack.

Table 4: Maximum w/c ratio for durability. Adapted from Table 2.5 of CIRSOC 201 (2005).

Maximum w/c ratio	**Types of exposure of structures**									
	A1	**A2**	**A3 y M1**	**CL y M2**	**M3**	**C1**	**C2**	**Q1**	**Q2**	**Q3**
Unreinforced concrete	---	---	---	0.45	0.45	0.45	0.40	0.50	0.45	0.40
Reinforced concrete	0.60	0.50	0.50	0.45	0.40	0.45	0.40	0.50	0.45	0.40
Prestressed concrete	0.60	0.50	0.50	0.45	0.40	0.45	0.40	0.50	0.45	0.40

The fact of achieving low w/c ratios in the design of a concrete would make it possible to achieve a cementitious matrix that is less permeable to the pore solution and consequently, to a greater difficulty for the displacement of electrons in the microstructure of the concrete. This situation was observed in the resistivity values obtained, where it increased when the w/c ratio decreased. For their part, Van Noort et al. (2016) who evaluated, among other effects on resistivity, that of the w/c ratio, observed that the effective water content in a fresh concrete mix controls the resistivity of hardened concrete. Therefore a decrease in the w/c ratio a constant cement content will result in an increase in resistivity.

Particularly for the case of pastonada P-0x, the limitation to the maximum w/c ratio inferred by extrapolation of the experimental results, corresponds to the limit value indicated by the Argentine regulations. Said referred limit value is one of the durability requirements to be considered in the design of reinforced and prestressed concrete against the corrosion mechanism.

The pozzolanic reaction would give rise to a decrease in the concentration of $Ca(OH)_2$, and with it, to a lower ionic charge in the pore solution, thus resulting in the pastes made with pozzolanic cement showing the highest resistivities. On the other hand, said pozzolanic activity would allow a refinement of the pores, restricting their connectivity and increasing the resistance to the flow of electric current. Similar results were obtained by Medeiros-Junior and Lima (2016) when they evaluated the resistivity in concretes made with four types of commercially available cements in Brazil, including fillerized and pozzolanic cement.

Regarding the use of the water repellent additive, its null or counterproductive effect in some cases could be due to the presence in its chemical composition of sodium and calcium, which would be contributing to a greater ionic charge in the pore solution. It is not reported in the review of the state of the art considered in the present investigation, the effect of water repellents on resistivity.

5. CONCLUSIONS

Based on the study carried out and the interpretation of the results obtained, the following conclusions are presented:

- For the w/c ratios used, it was possible to establish that the higher the w/c ratio, the lower the resistivity.
- Designing a durable concrete against a degradation mechanism that involves steel corrosion would imply the use of w/c ratios, at least not greater than 0.45.
- Regarding the types of cements used, the pastonadas made with CPP had a better performance than those made with CPF.
- In general, the use of the water repellent additive had an effect between null and slightly counterproductive in the electrical resistivity values measured in the saturated state.
- Finally, the evaluation of electrical resistivity turns out to be a simple and expeditious test methodology, allowing the evaluation of a property of great importance for the interpretation of the durability of reinforced and/or prestressed concrete.

6. ACKNOWLEDGMENTS

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