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Concrete resistivity values for chloride resistance classes.

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ABSTRACT

The electrical resistivity of concrete represents its porosity and tortuosity. For years, the use of this parameter has been proposed due to its ease of measurement (non-destructive) on the same specimen used for compressive strength testing and both as a corrosion indicator and because of its equivalence to the chloride diffusion coefficient. The latest version of Eurocode 2 (EC2) for concrete introduced the Exposure Resistance Classes (ERCs) concept, which allows concrete to be classified by its diffusion coefficient in a standardized test or by its resistance to carbonation. In this work, a simplified equivalence between resistivity and the apparent chloride diffusion coefficient has been applied to obtain the ERC's table based on resistivity. The model for calculating cover requirements has also been simplified, requiring only the resistivity, aging exponent and exposure factor.
Keywords: concrete; service-life; corrosion; resistivity; exposure resistance classes.

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Valores de Resistividad para clases de resistencia a los cloruros.

RESUMEN

La resistividad eléctrica del hormigón representa su porosidad y tortuosidad. Desde hace años se ha propuesto el uso este parámetro debido a su facilidad de medida (no destructiva) en la misma probeta que se usa para el ensayo de resistencia a la compresión y tanto como Indicador de corrosión como por su equivalencia con el coeficiente de difusión de los cloruros. En la última versión del Eurocódigo 2 (EC2)-hormigón se han introducido las "Clases de Resistencia al ambiente" (Exposure Resistance clases, ERC en sus siglas en inglés) que permiten clasificar a los hormigones por su coeficiente de difusión en ensayo normalizado o por su resistencia a la carbonatación. En el presente trabajo se ha aplicado una equivalencia entre la resistividad y el coeficiente de difusión aparente de los cloruros simplificada para obtener la tabla de ERC's basada en la resistividad. Para el cálculo de los recubrimientos también se ha simplificado el modelo que necesita solo como parámetros de entrada la resistividad, el exponente de edad y el factor de exposición.

Palabras clave: hormigón, vida-en-servicio, corrosión, resistividad, clases de resistencia al ambiente.

Valores de resistividade do betão para as classes de resistência aos cloretos.

RESUMO

A resistividade elétrica do concreto representa sua porosidade e tortuosidade. Há anos, o uso desse parâmetro tem sido proposto devido à facilidade de sua medição (não destrutiva) no mesmo corpo de prova utilizado para o ensaio de resistência à compressão, tanto como indicador de corrosão quanto por sua equivalência ao coeficiente de difusão de cloretos. A versão mais recente do Eurocódigo 2 (EC2) para concreto introduziu as Classes de Resistência à Exposição (ERCs), que permitem classificar o concreto pelo seu coeficiente de difusão em um ensaio padronizado ou pela sua resistência à carbonatação. Neste trabalho, uma equivalência simplificada entre resistividade e o coeficiente de difusão aparente de cloretos foi aplicada para obter a tabela de ERCs baseada na resistividade. O modelo para o cálculo dos requisitos de cobrimento também foi simplificado, exigindo apenas resistividade, expoente de idade e fator de exposição como parâmetros de entrada.

Palavras-chave: betão, vida útil, corrosão, resistividade, classes de resistência ao ambiente.

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1. INTRODUCTION

Reinforcing steel corrosion is the process that produces the greatest number of deteriorations in structural concrete. To prevent premature deterioration due to corrosion, codes establish the following requirements based on the type of environment: a) minimum cover thicknesses, b) proportions of the mix components or a minimum compressive strength, c) prohibition of the use of chlorides in the mix, and d) limits on flexural crack width. In recent years, in addition to these requirements, there has been a growing interest in adjusting mix designs by using performance tests (resistance to chlorides and carbonation) and then applying models to calculate the time to corrosion of the reinforcement.

These models for predicting the progression of chlorides or carbonation were proposed many years ago; among them some already well-known to researchers are still valid (Tuutti 1982, Andrade 1989, 2014; Sagües 2003; Izquierdo 2001). These models require as input parameters test results that have been slowly standardized (ASTM C1556; EN 12390-11) and have led to what are called “Durability Indicators” (Baroguel-Bouny 2002, Andrade 2006), which establish certain limit values for each cover depth and service life. Due to the difficulty and cost of these tests, since the 1990s, models based on electrical resistivity have also been proposed. Resistivity is a non-destructive method (Andrade 1993, 2004) and therefore much more practical and accessible to laboratories.

As mentioned, the effective incorporation of models or indicators into standards remains very slow, although models were incorporated into the Annexes of the Spanish structural concrete Code in 2008 (EHE 2008). Another novelty is that the cover depths of the new version of Eurocode 2 (EC-2) (EN 1992-1-1) for structural concrete have been calibrated using models (Andrade & Izquierdo 2023), but these models have not been incorporated into the standard. In other words, the calculation models have been considered implicitly. The reason for not suggesting a specific model is due to international caution regarding the accuracy and uncertainty of the predictions, given the lack of long-term calibration of the available durability models.

A step towards incorporating service life indicators and models into the standard is being taken within the CEN TC-104-Concrete (EC2) committee with the proposal of the "Exposure Resistance Classes (ERC)" concept, which will allow for classification based on the results of performance tests. This paper briefly explains this concept and illustrates both the resistivity-based model and its simplification, as well as the resistivity values that are consistent with the ERC levels that have been proposed for chloride resistance.

2. TECHNICAL PROCEDURES

The concept of ERC, as approved by the EC2 (EN 1992-1-1) Durability Committee (CEN-TC250/SC2/WG1/TG110), is described first. Then, the test methods for determining chloride resistance values and the resistivity are given. Finally, the method used to derive resistivity from diffusion coefficient values based on the models employed is explained.

2.1 ERC Concept

In European regulations, potential deterioration processes are classified based on Exposure Classes (named as XC). For reinforcement corrosion, these are designated XC for carbonation, XS for marine chloride environments, and XD for chlorides from other sources, such as de-icing salts. The EC2-2023 exposure classes remain virtually the same as those in the standard for concrete as a material (EN 206). Exposure Resistance Classes (ERC) define concrete resistance to each of these exposure classes. The concept has only been developed for reinforcement corrosion, but it is as well intended to be applied to other types of attack.

The agreed-upon symbols for the ERCs were XRC for carbonation resistance and XRDS for chloride resistance, whether marine or from de-icing salts. It is important to note that XRC (Resistance to Carbonation Exposure) should not be confused with XC (Carbonation Exposure), as the latter classifies the aggressiveness of the environment, while XRC represents the degree of resistance to that XC.

It is also important to point out that there is a "corrosion limit state" accepted for the ERCs that is not the depassivation of the reinforcement, as this is almost impossible to be detected with precision. Instead, it was agreed that a certain propagation period should be incorporated within the service life. This period was conventionally set at a corrosion depth of 50 µm in the case of carbonation (uniform) corrosion and 500 µm pitting depth (localized corrosion) in the case of chlorides. Therefore, the service life consists of an initiation period and a propagation period, as Tuutti (Tuutti 1982) reflected in his diagram.

To ensure a smooth transition from the current system, based on specifying the concrete composition, to the use of ERC's, a transition period was established where both systems can coexist. Therefore, carbonation or chloride tests are not mandatory for all mixes; ERCs can also be met through the concrete composition. The novel aspect is the establishment of limits in the test results of this new ERC system.

2.1.1 EC2 Covers

The cover values for each ERC for chloride attack are presented in table 1. These values may be adjusted by each country according to its experience.

Table 9. Minimum cover thicknesses ($c_{min,dur}$) for chloride exposure classes (EN 1992-1-1:2023).

ERC	Exposure Classes (chlorides)											
	XS1		XS2		XS3		XD1		XD2		XD3	
	Nominal service life (years)						Nominal service life (years)					
	50	100	50	100	50	100	50	100	50	100	50	100
XRDS 0,5	20	20	20	30	30	40	20	20	20	30	30	40
XRDS 1	20	25	25	35	35	45	20	25	25	35	35	45
XRDS 1,5	25	30	30	40	40	50	25	30	30	40	40	50
XRDS 2	25	30	35	45	45	55	25	30	35	45	45	55
XRDS 3	30	35	40	50	55	65	30	35	40	50	55	65
XRDS 4	30	40	50	60	60	80	30	40	50	60	60	80
XRDS 5	35	45	60	70	70	—	35	45	60	70	70	—
XRDS 6	40	50	65	80	—	—	40	50	65	80	—	—
XRDS 8	45	55	75	—	—	—	45	55	75	—	—	—
XRDS 10	50	65	80	—	—	—	50	65	80	—	—	—

NOTE 1: XRC classes for resistance against corrosion induced by carbonation are derived from the carbonation depth [mm] (characteristic value 90 % fractile) assumed to be obtained after 50 years under reference conditions (400 ppm CO2 in a constant 65 %-RH environment and at 20 °C). The designation value of XRC has the dimension of a carbonation rate [mm/√(years)].

NOTE 2: The recommended minimum concrete cover values $c_{min,dur}$ assume execution and curing according to EN 13670 with at least execution class 2 and curing class 2.

NOTE 3: The minimum covers can be increased by an additional safety element $\Delta c_{dur,\gamma}$ considering special requirements (e.g. more extreme environmental conditions).

2.2 Testing standards to be used.

To determine whether a concrete belongs to one XRC or another, performance tests are necessary. The European standards for natural conditions (reflecting the test conditions of an XS2 or XD2 environment with constant humidity) and for accelerated testing in the case of chlorides are:

- EN12390-11 – "Testing hardened concrete - Part 11: Determination of the chloride resistance of concrete, unidirectional diffusion". This standard is that of natural diffusion over 90 days after 28 days of moist curing in contact with a 3% by mass NaCl solution.
- EN12390-18 – "Testing hardened concrete - Part 18: Determination of the chloride migration coefficient". It contains an accelerated method as alternative to the longer natural diffusion test.

2.2.1. Resistivity.

EN12390-19 – "Testing hardened concrete - Part 19 - Determination of electrical resistivity". The resistivity standard indicates the reference method and the use of the four-point metho. It is similar to Alconpat Recommendation.

2.3 Models for calculating cover requirements

In the EC2 committee, various models were used for the calculation, including those of the *fib* Model Code (MC2020) (Andrade & Izquierdo 2023), which are the ones that will be used in this work. Once the depths of the aggressive front were obtained, the cover depths were adjusted in a consensual and rational manner, since the progression between ERC's classes should be between 5 and 10 mm, and not with smaller fractions.

2.3.1 Resistivity Model

This communication does not detail the classical carbonation or chloride models, which are those proposed in MC2020 with varying input parameters, but it does describe the resistivity model due to its novelty.

Resistivity can be used as a durability indicator, as can the chloride diffusion coefficient or the carbonation rate. The complete resistivity-based model is formulated for the initiation and propagation periods as expressed in equation (1) (Andrade 2004).

$$- \quad t_L = \frac{c^2 \cdot \rho_{ef,0} \cdot S_W^{-\tau} \cdot \left(\frac{t_n}{t_0}\right)^q}{F_{xc}} \cdot r + \frac{P_{lim} \cdot \rho_{ef,t} \cdot \left(\frac{t_n}{t_0}\right)^q \cdot S_W^{\tau}}{K_{corr}} \qquad (1)$$

Where:

- c is the minimum cover thickness, in cm.
- $\rho_{ef,0}$ is the effective resistivity at 28 days of curing, in Ω·cm.
- q is the age factor (-). This factor is 0.8 times the diffusion coefficient (Andrade et al., 2011).
- t_0 is the first 28-day age at which the resistivity value is taken.
- t_n is the last age measured. Both ages t_0 and t_n must be entered in the same units.
- F_{xc} is the environmental exposure factor for the initiation period, in $cm^3 \cdot \Omega$/year.
- P_{lim} is the corrosion penetration considered as the limit. For a 0.1 mm crack width on the concrete surface, a bar diameter loss of 500 µm is used.
- S_w, is the degree of saturation of the concrete. It depends on the tortuosity τ, which, for average purposes, can be taken as having a value of 2. This S_w factor depends on the

climate, whether the concrete is directly exposed to rain, and the porosity/quality of the material.
- K_{corr} is the proportionality factor between the corrosion rate and the inverse of the resistivity, 30.16 Ω·cm²/year.

In the case of chlorides, applying this model involves calculating the three factors of the initiation period: a) reaction or combination of chlorides, "r"; b) environmental factor, "F_{xc}"; and c) evolution with age, "q". For the propagation period, the following factors also apply: age, q, and the degree of saturation, S_w. This must S_w be considered in both the initiation and propagation periods, or alternatively, an average resistivity value can be introduced for each exposure class.
figure 1 shows a diagram of the increase in resistivity with time and its cyclic evolution because the seasonal humidity changes. The figure assumes that one exposure class is submerged (saturated concrete) and another is in the atmosphere, where resistivity will be higher because the degree of saturation S_w is smaller.

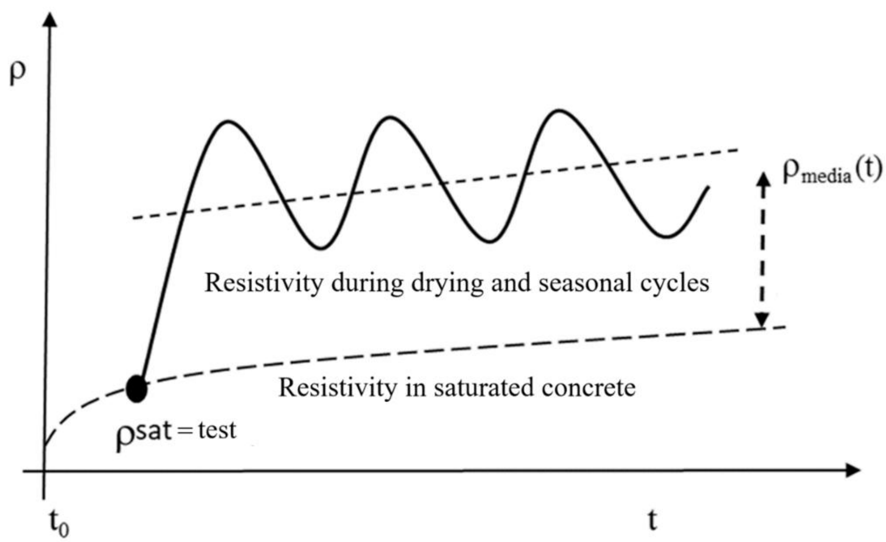

Figure 1. Schematic evolution of resistivity over time as a function of ambient humidity.

Table 2 presents the environmental factor F_{xc} values for chlorides as a function of EC2 exposure classes, considering the use of the apparent diffusion coefficient. The reaction factor, r, can be included within this environmental factor, as will be explained later. Similarly, the age factor q can be assumed based on the type of cement (tables 3 and 4), or it can be determined experimentally by recording its evolution over time (figure 1).

Table 2. Exposure factors F_{xc}.

Exposure Class	**XDS1**	**XDS2**	**XDS3**
F_{exp} (Ωcm³/año)	10000	17000	25000

2.4 Simplified Model Based on Resistivity

It is possible to simplify equation (1) for the propagation period in the case of chlorides. Instead of calculating it, a propagation period of 5 years can be adopted, for exposures XS2 or XD2 (always saturated), which would leave t_i = 45 years for a service life of 50 years.
Regarding the initiation period, the effect of the chloride reaction with the cement phases (reaction factor, r) can be incorporated into the environmental coefficient value in equation (2). The effect of the chloride reaction on the environmental factor, which is F_{xc} = 1E-4 Ωcm³/s, can be obtained

from the natural diffusion (or migration) test by multiplying (equation (2)) the resistivity measured in the same specimen by the D_{ap}:

$$F_{xc} = \rho_{ef} \cdot D_{ap} \qquad (2)$$

To calculate the depth of the critical chloride front or the coating thickness, once this equivalence of equation (2) is assumed, it is possible to apply the square root of time law, which underlies any diffusion process (as was done to develop equation (1)). This results in equation (3):

$$x_{Cl} = 2 \cdot \sqrt{D_{ap,t} \cdot t} = 2 \cdot \sqrt{\frac{7{,}5\ E{-}4}{\rho_{ef,t}} \cdot t} \qquad (3)$$

The value of $F_{xc} = 7.5 \times 10^{-4}$ is applicable for natural diffusion tests. In the case of accelerated migration tests, given the short duration of the test and the fact that chlorides practically do not combine, the value that should be used is $F_{xc} = 13 \times 10^{-4}$.

The calculation of the ageing factor can be made by the simple following of the evolution of resistivity over time (ideally between 28 or 90 days plus the 90 days of the test). By fitting this evolution, the age exponent q is obtained. The formula to be applied is that expressed in equation (3).

$$\rho_{ef,t} = \rho_{ef,0} (\frac{t}{t_0})^q \qquad (4)$$

This simplified formulation, which only requires calibrating the resistivity with the apparent diffusion coefficient (due to the reaction of chlorides with the cement phases) and monitoring the resistivity value up to a predetermined age, is readily applicable in practice. Therefore, it has been applied to diffusion coefficient values obtained from probabilistic models, as explained below.

3. RESULTS

The designations for the final ER classes for chlorides are shown in the first column of table 6 (EN 1992-1-1-2023). Ten ERC levels have been identified, which can be combined or further subdivided as determined by national standards bodies based on their local experience.
The following columns of Table 3 show diffusion coefficient values that classify the ERC levels. These values are not yet agreed upon, and those shown are those proposed by the author of this work based on:

- Considering the ERC designation values as average diffusion coefficient values. Therefore, the characteristic values would be determined by the coefficient of variation (CV) obtained in the test, suggesting that a batch should not be accepted if the CV > 30%.
- Since the D_{ap} coefficient decreases over time (evolution with age, factor α), the coefficient values obtained from equation (4) for α = 0.3, 0.4, 0.5, and 0.6 are also specified.
- The cover depth values, in accordance with the definition indicated in note 1 of table 1, were obtained through probabilistic calculations using the MC2020 chloride model from *fib* to represent a corrosion probability of 7-10%.

Table 3. Average values of the diffusion coefficient* D_{ap} in [cm^2/s] for XRDS classes based on natural diffusion tests (EN 12390-11) for environments with chlorides.

Mean value of the apparent diffusion coefficient for several ageing exponents (50 years' service life and t_0 = 28 days) $\times 10^{-12}$ m^2/s*					
Value of α during 50 years	**α ≥ 0,0**	**α ≥ 0,3**	**α ≥ 0,4**	**α ≥ 0,5**	**α ≥ 0,6**
Type of cement as European denomination*	**CEM I** Low in aluminates	**CEM I** High in aluminates	**CEM II** (<20% addition)	**CEM IV** (< 40% addition)	**CEM III** (35-80% slags)
XRDS0,5	0,05	0,35	0,7	1,3	2,5
XRDS 1	0,1	0,7	1,4	2,6	4,9
XRDS1,5	0,15	1,05	2	3,9	7,3
XRDS 2	0,2	1,4	2,7	5,1	9,8
XRDS 3	0,3	2,1	4	7,7	14,6
XRDS 4	0,4	2,8	5,3	10,2	19,5
XRDS 5	0,5	3,5	6,7	12,8	24,4
XRDS 6	0,6	4,2	8	15,3	29,3
XRDS 8	0,8	5,6	10,7	20,4	39
XRDS 10	1	7	13,4	25,5	48,8

*Suggestion from the author. Not yet approved at European level.

Applying equation (3) to these values and using a value of $F_{xc} = 7.5 \times 10^{-4}$ yields the equivalent resistivity values shown in table 4.

Table 4. Average resistivity values (Ω·m) for chloride environments at 28 days according to EN 12390-19 (In the case of resistivity, the CV is approximately 15%).

Mean values of resistivity (Ω·m) for several ageing exponents using a value of F_{xc}= 7,5x10-4 (50 years service life and t_0 = 28 days)					
Value of α during 50 years	**α ≥ 0,0**	**α ≥ 0,3**	**α ≥ 0,4**	**α ≥ 0,5**	**α ≥ 0,6**
Type of cement as European denomination *	**CEM I** Low in aluminates	**CEM I** High in aluminates	**CEM II** (<20% addition)	**CEM IV** (< 40% addition)	**CEM III** (35-80% slags)
XRDS 0,5	15000	2150	1071	577	300
XRDS 1	7500	1070	535	288	155
XRDS1,5	5000	715	375	192	105
XRDS 2	3750	535	280	147	77
XRDS 3	2500	357	188	98	52
XRDS 4	1875	268	140	75	40
XRDS 5	1500	215	112	60	30
XRDS 6	1250	180	94	50	25
XRDS 8	937,5	134	70	37	20
XRDS 10	750	107	56	30	15

*Suggestions of the author

Table 5. Cover depths (mm) according to EC2 and resistivities (Ω·m) equivalent to the apparent diffusion coefficients deduced from the ERC's for α = 0.3 and the environmental factors Fxc from the table 2.

ERC D_{ap} **(×10⁻¹² m²/s)** ***ρ (Ω·m)***	**Exposure classes (chlorides for α = 0,3) c (mm); Resistivity (Ω·m)**					
	XS1/XD1		**XS2/XD2**		**XS3/XD3**	
	Service life (years)					
	50	**100**	**50**	**100**	**50**	**100**
XRDS 0,5	20	20	20	30	30	40
D_{ap}=*0,35*→*ρ*	***914***		***1550***		***2260***	
XRDS 1	20	25	25	35	35	45
D_{ap}=*0,7*→*ρ*	***460***		***780***		***1130***	
XRDS 1,5	25	30	30	40	40	50
D_{ap}=*1,05*→*ρ*	***305***		***515***		***760***	
XRDS 2	25	30	35	45	45	55
D_{ap}=*1,4*→*ρ*	***230***		***390***		***570***	
XRDS 3	30	35	40	50	55	65
D_{ap}=*2,1*→*ρ*	***155***		***260***		***380***	
XRDS 4	30	40	50	60	60	80
D_{ap}=*2,8*→*ρ*	***115***		***195***		***290***	
XRDS 5	35	45	60	70	70	—
D_{ap}=*3,5*→*ρ*	***95***		***155***		***230***	
XRDS 6	40	50	65	80	—	—
D_{ap}=4,2→*ρ*	***80***		***130***		***190***	
XRDS 8	45	55	75	—	—	—
D_{ap}=*5,6*→*ρ*	***60***		***97***		***145***	
XRDS 10	50	65	80	—	—	—
D_{ap}=*7*→*ρ*	***50***		***80***		***115***	

As an example, table 5 also calculates the resistivities equivalent to the apparent diffusion coefficients of Table 3, but using the environmental factors in table 2, instead of using a value of $F_{xc} = 7.5 \times 10^{-4}$. The example was performed for an ageing exponent α = 0.3. In this table, for ease of use, the minimum resistivity values have been added below the Eurocode 2 cover depth values, using the environmental factors in table 2 for the equivalence.

4. DISCUSSION

It is now accepted that time-to-corrosion prediction models are not calibrated for the long term, so their accuracy or uncertainty will remain unknown until sufficiently long experience is available to compare short-term tests with 50- or 100-year results. An additional source of uncertainty is the environment, since, although the values are grouped into exposure classes (XCs), many variations in humidity and temperature can occur locally within the same environment. While assuming this uncertainty in the prediction, a full consensus was reached in the CEN-TC250/SC2/WG1/TG10 Committee, which used five different chloride models with varying input parameters. The cover depths in Table 1 were obtained by rounding the raw chloride penetration results of these models to ensure that the ERC jumps were 5 or 10 mm, rather than fractions. Therefore, the coating thicknesses proposed in Table 3 are not solely the result of an exact mathematical calculation, but they also incorporate rounding and expert opinion. Furthermore, these cover depths correspond to the minimum depth provided by the nominal value, plus a tolerance margin of 5 or 10 mm. Consequently, any attempt to reproduce the values in table 1 may lead to discrepancies. In any case, these cover depths are very similar to those that existed in the previous version of Eurocode 2 (EN 1992-1-1:2023) and can be adapted by each country according to its local experience.

As an example,
In the case of resistivity, once calibrated with initial natural chloride diffusion tests and using expression (2), determined for each type of concrete, the practical advantage of being an inexpensive and non-destructive method allows quality control to be extended to a much larger sample population. This was the methodology applied in the construction of the third set of locks of the Panama Canal (Andrade et al. 2016), which saved the need for countless chloride tests.

4.1 Simplified calculation of cover depths
Although, as mentioned, the cover depths were calculated using models that employed average values of the apparent chloride diffusion coefficient, with various CVs and assuming a failure probability of 7-10%, three cases are presented below demonstrating that these coatings can also be approximately deduced from a very simplified calculation.
Applying equation (3) to Table 6, the cover depths for classes XRDS1, XRDS3, and XRDS10 are shown as examples for exposure class XS2, which corresponds to total immersion conditions (the same as those of the natural diffusion test). The example cover depths are for 50 years, and the resistivity or apparent diffusion coefficient values are without an age exponent ($\alpha = 0$).

Table 6. Cover depths for class XS2 and 50 years, and those obtained with the simplified calculation of the square root of time using an F_{xc} value of 17000 (Table 2).

Class ERC	**Minimum cover depth (mm) in Table 1 for class XS2 and 50 years with α=0**	**Resistivity value ($\Omega \cdot m$)**	**Depth (mm) Calculated with Eq. (3) and 50 years with α=0**
XRDS1	25	7500	25,1
XRDS3	40	2500	43,5
XRDS10	80	750	79,4

It can be verified that the cover depth values proposed in Table 1 by EC2, given that they are assumed for a 7-10% probability of failure, are reasonably close to those that can be calculated in a simplified manner using equation (3). This applies both to the apparent diffusion coefficient and the equivalent resistivity. The additional 5 or 10 mm must always be applied to these cover depths, as these are minimum values, which absorbs the discrepancy due to the necessary rounding to multiples of 5 or 10. This simplified calculation allows the designer to approximate their specific case without the need for probabilistic calculations.

5. CONCLUSIONS

The use of electrical resistivity as an indicative parameter of chloride resistance is an increasingly widespread practice, but it requires reference values related to cover depths and consideration of the increase in resistivity over time.

This paper presents a simplified method for obtaining the environmental factor, F_{xc}, from a simultaneous chloride diffusion and resistivity test, while monitoring the increase in resistivity over time to determine an age factor between 28 and at least 90 days. Based on the equivalence between resistivity and apparent diffusion coefficient (natural or migration test), the necessary cover depths can be calculated in a simplified manner using the square root of time law. These simplified calculations are an engineering approximation that will assist the designer.

Thus, the minimum resistivity limits equivalent to the apparent diffusion coefficients are provided for the resistivity reference values (ERCs) used in Eurocode 2 (EN 1992-1-1:2023).

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