POROSITY AND ELECTRICAL RESISTIVITY-BASED EMPIRICAL CALCULATION OF THE OXYGEN
DIFFUSION COEFFICIENT IN CONCRETE

P. Linares*, C. Andrade and D. Baza

Eduardo Torroja Institute for Construction Science (IETcc).
National Research Council
Serrano Galvache, 4
Madrid, Spain
website: <http://www.ietcc.csic.es>
* e-mail: plinares@ietcc.csic.es

Keywords: Concrete, diffusion, porosity, oxygen, resistivity.

ABSTRACT

Concrete carbonation induced by gas transport has an adverse effect on the service life of the steel-reinforced material. Gas tightness is crucial where concrete is used to contain radioactive materials and of utmost importance where acting as a radon barrier. Since as a rule gas travel inside concrete is governed either by diffusion or permeability, the material's performance in that respect is assessed by analysing those two parameters.

The gas diffusion coefficient in concrete is not readily found, however, due to the practical difficulties involved in preventing gas from leaking out of standard diffusion cells. An alternative approach is to measure permeability at high gas concentration and pressure. The existence of a relationship between the oxygen diffusion coefficient and permeability in OPC concrete was established by the authors in a previous paper.

Diffusion has also been shown to be related to porosity and, in solutions, to electrical resistivity. Little is known, however, about the relationship between gas diffusion and resistivity where the pores may be filled not with a liquid, but with air. Inasmuch as resistivity is a non-destructive technique and porosity a property that can be readily measured, these two parameters could be used to directly assess concrete durability, its performance in nuclear facilities and its suitability as a radon barrier.

This paper describes a study conducted to formulate equations from which to analytically determine the oxygen diffusion coefficient. These equations are derived from empirical measurements of oxygen diffusion coefficient, concrete porosity and electrical resistivity. The findings, which corroborate the existence of such relationships, were used to formulate an equation to calculate the diffusion coefficient directly from the experimental values of concrete porosity and resistivity.

Since porosity depends primarily on concrete batching, curing and moisture content, two OPC concrete mixes were prepared using different water/cement ratios and two curing conditions. The combination resulted in four types of concrete. Pre-conditioning at three values of relative humidity was subsequently deployed.

1.- INTRODUCTION

Diffusion is useful for characterising concrete resistance to gas permeation, a primary determinant of carbonation and gas tightness.

Reinforced concrete durability has been shown to be adversely affected by many factors¹, mechanical (overloading, vibration, earthquakes, impact), physical (frost, fire), biological (microorganisms, plants) and chemical (soil sulfates, chemicals). Whilst mechanical issues can be factored into structural analysis and design, the action of all the other agents depends primarily on the ingress of aggressive substances carried across concrete pores by gas or water. The mechanisms governing gas transport through concrete are the same as in any other porous medium: pressure head-induced permeation and concentration gradient-induced diffusion². The latter drives the transport of carbon dioxide, which carbonates the hydrated paste in the concrete cover. CO₂ diffusion is a key to the advance of the carbonation front and therefore to reinforced concrete durability.

Gas diffusion plays a significant role not only in concrete durability but also in its airtightness, which must be monitored in nuclear reactor containers and periodically tested to ensure the absence of leaks. It is likewise a determinant in another issue of growing concern, the radon released from rock and soil that accumulates in buildings^{3,4}.

Measuring the gas diffusion coefficient is challenging for want of standard procedures and the need to render the testing apparatus (normally a two-chamber diffusion cell) sufficiently airtight. In an attempt to solve that problem, in a recent study⁵ the authors related permeability, testing for which is standardised and widely referenced⁶, to gas diffusivity. In that context, the theoretical relationships between gas and liquid permeability and diffusivity established by TC 116-PCD constitute meritorious progress in the understanding of other features of substance transport through concrete⁷.

The difficulty involved in measuring gas diffusivity has driven the use of parameters other than the permeability coefficient (k) to characterise concrete resistance to gas transport, such as porosity (ϵ), including tortuosity, and (as in stone) electrical resistivity (ρ_e). Whilst correlations among these parameters in solutions have been described, no expression applicable to gases has yet been forthcoming. Potential relationships between the oxygen diffusion coefficient and electrical resistivity were explored in this study. Characterising the gas diffusivity of concrete on the grounds of resistivity would greatly simplify the approval process with a view to insulating buildings against radon and assessing concrete durability and performance in nuclear facilities.

2.- THEORETICAL FUNDAMENTALS

In past research⁸ one of the present authors proposed the use of resistivity to characterise service life based on Einstein's law that relates the movement of electrical charges to the conductivity/resistivity of the medium⁹:

$$D = \frac{n}{\rho_e} \quad [1]$$

where D is the effective or steady-state diffusion coefficient [cm²/s], n is a constant dependent on the concentration of the external aggressive agent and ρ_e is electrical resistivity (of water-saturated concrete in the new model) [$\Omega \cdot \text{cm}$].

That equation has been applied to electrolytes¹⁰, for ion travel can be likened to that of electrical charges. The feasibility of applying Equation [1] to model gas transport was explored in this study, assuming that, although gas molecules are not electrically charged, their mobility can be quantified and modelled in much the same way as the components of electrolytes.

A second advantage to Equation [1] is that concrete resistivity can either be measured directly or calculated from porosity as per the modified Archie's law¹¹ (Equation [2]):

$$\rho_e = \rho_0 \cdot \epsilon^{-\tau} \quad [2]$$

where ρ_0 is the electrical resistivity of the pore aqueous phase (approximately $0.5 [\Omega \cdot \text{m}]$) and ε^τ is tortuous porosity, a parameter used in this study to combine porosity and tortuosity.

Another equation tested, based on pore diameter, was derived earlier¹¹ by analogy to a modified version of Archie's law:

$$\emptyset = \emptyset_0 \cdot \varepsilon^{-\tau} \quad [3]$$

where $\emptyset_0$ is the minimum pore diameter in MIP (mercury intrusion porosimetry) and $\emptyset$ may be either the threshold $\emptyset_{th}$ or the mean $\emptyset_m$ pore diameter, both of which are identified in Figure 1.

Figure 1. MIP measurement of cumulative porosity, showing the threshold and mean pore diameter values

In a nutshell, if gas diffusivity can be related to resistivity (Equation [1]), the former can likewise be related to the pore microstructure in concrete.

3.- MATERIALS AND METHODS

3.1.- Materials

The 75 mm diameter (surface area = 0.0044 m^2) cylindrical concrete specimens prepared were cut into 50 mm thick slices.

The two ordinary portland cement-based concrete mixes studied were designed with different w/c ratios (Table 1), inasmuch as that factor is a determinant in concrete porosity and its diffusion coefficient¹².

The concretes were batched to cover the range of mixes routinely used in construction in Spain, as listed in Table 1.

Table 1. Concrete mixes used in the study

Concrete mix	Cement [kg/m ³]	Cement type	Water [kg/m ³]	W/C ratio	Gravel (4/11) [kg/m ³]	Sand (0/4) [kg/m ³]	Admix-ture* [kg/m ³]	Paste fraction γ
1	300	CEMI 42.5 R	165	0.55	928	994	0	0.65
2	400	CEMI 42.5 R	166	0.41	886	957	2	0.67

*Rheobuild 1000

Given that gas transport in concrete is primarily governed by the porosity of the material and that curing affects porosity¹³ significantly, each concrete mix was cured under two conditions:

1. 'dry' chamber curing (>98 % RH) for 2 d followed by 26 d in a laboratory environment (50 % RH)
2. 'wet' chamber curing (>98 %) for 28 d.

The characteristics of the four resulting concretes studied are summarised in Table 2.

Table 2. Types of concrete tested

Concrete mix	Curing conditions	Label (kg/m ³ -W/C-curing)
1	Dry	300-0.55-2 d
	Wet	300-0.55-28 d
2	Dry	400-0.41-2 d
	Wet	400-0.41-28 d

As the table shows, the concretes were labelled in keeping with the amount of cement used (kg/m³), w/c ratio and days cured in a humidity chamber.

Since in addition to cement content, w/c ratio and curing, moisture in concrete pores has a significant effect on gas transport^{14,15}, the concretes prepared were preconditioned to three relative humidity values: 50 % (laboratory environment), 75 % and 84% RH (both in humidity chambers), using specific salt solutions as recommended in European standard EN 83966¹⁶ substituting KCl for NaCl in the 84 % material.

The aforementioned combinations yielded a total of 12 sample materials.

3.2.- Procedures

The cured samples were stored in humidity chambers until they reached a constant weight, when they were tested in a diffusion cell. Resistivity values were measured immediately prior to diffusion testing to ensure that the two tests were conducted on the same concrete microstructure for the intents and purposes of correlation.

Electrical resistivity was found experimentally as recommended in European standard EN 83988-1:2008¹⁷, while the diffusion coefficient was determined using a custom-made diffusion cell and the methodology described below.

3.3.- Porosity

Samples dried to a constant weight in a laboratory environment were tested for porosity with mercury intrusion porosimetry (MIP) as specified in ASTM-D4404¹⁸. In MIP analysis, mercury is injected into the concrete at high pressure as the volume absorbed is monitored.

At least three samples of each type of concrete, ranging in mass from 0.69 g to 1.78 g, were tested on a Micromeritics Autopore IV 9500 VI.05 porosimeter with 14.300 advancing and receding contact angles. The arithmetic mean of the three measurements were used in the calculations.

Inasmuch as MIP calls for small samples (1 cm³ cubes), the materials used contained no coarse aggregate, but only fines (grain size <5 mm). In other words, although MIP-determined porosity is normally reported to refer to concrete, it is in fact a measure of the porosity in the mortar (cement, fines and water).

As mentioned in section 2, in addition to porosity (ε) this study explored the effect of tortuous porosity (ε^t) calculated:

1. from the modified version of Archie's law in which ρ_0 is the electrical resistivity of water (Equation [2])
2. from a relationship derived from the aforementioned law based on pore diameters (Equation [3]).

3.4.- Diffusion coefficient

Experiments were conducted to find the diffusion coefficients by sealing the concrete samples into the open end of a custom-made airtight diffusion half-cell (Figure 2), into which nitrogen was streamed to establish quasi-null oxygen concentration. The oxygen content readings taken in the chamber during the test afforded a measure of the amount of gas diffused from the exterior environment across the sample.

Oxygen content was monitored with galvanic cell-based sensors that generated a voltage directly proportional to the oxygen concentration.

Figure 2. Experimental apparatus

As this cell was custom-made for these experiments, it was subjected to two airtightness tests.

First, the entire cell was tested for possible leaks by streaming nitrogen into the closed chamber to a null oxygen concentration and subsequently monitoring any fluctuations in oxygen content. As no rise was recorded, the cell was deemed to be airtight.

The seal around the sample was then tested for airtightness with a sample wrapped in a double layer of aluminium foil and proceeding as above. A small amount of oxygen was observed to enter the cell. As the air ingress rate was calculated to be smaller than the $3.78 \times 10^{-3} \cdot \text{h}^{-1}$ ceiling laid down in international standard ISO/DTS 11665-13¹⁹, the seal was regarded to be sufficiently airtight and the leak dismissed.

The steady state diffusion coefficient for the samples was found from Fick's first law:

$$J = -D \frac{\partial n}{\partial x} \quad [4]$$

where J is the rate of oxygen diffusion [$\text{mol}/\text{m}^2 \cdot \text{s}$] and $\frac{\delta n}{\delta x}$ is the oxygen concentration gradient [mol/m^4].

Where empirical data are at hand, into Equation [4] can be rewritten as:

$$\frac{(N_{O_2})_{t_{n+1}} - (N_{O_2})_{t_n}}{S \cdot (t_{n+1} - t_n)} = -D \frac{\frac{(\bar{N}_{O_2})_{C_E}}{V_{C_E}} - \frac{(\bar{N}_{O_2})_{C_R}}{V_{C_R}}}{L} \quad [5]$$

where $(N_{O_2})_{t_n}$ is the molar quantity of oxygen in the reception chamber at time n [moles]; S is the area of the exposed surface of the sample [m^2], $(\bar{N}_{O_2})_{C_i}$ is the experimentally found mean molar quantity of oxygen in chamber i (in time interval $n, n+1$) [moles], with E as source and R as reception; V_{C_i} is the volume of chamber i [m^3]; and L is sample height [m].

Here, a source chamber was not needed because the oxygen in the surrounding air was used as the source. Since oxygen molarity in the air is a constant ($9.3 \text{ mol}/\text{m}^3$), equation [5] could be rewritten as:

$$\frac{(N_{O_2})_{t_{n+1}} - (N_{O_2})_{t_n}}{S \cdot (t_{n+1} - t_n)} = -D \frac{9.3 - \frac{(\bar{N}_{O_2})_{C_R}}{V_{C_R}}}{L} \quad [6]$$

The diffusion coefficients shown are the arithmetic means of the values measured in at least two samples of each type of concrete.

3.5.- Electrical resistivity

The direct (reference) method for measuring electrical resistivity described in EN 83988-1:2008 was used. In that method, a resistivity meter is used to measure concrete resistance to the flow of a uniform electrical current generated by two electrodes connected to parallel sides of the specimen.

Resistivity was measured both 28 d after the specimens were cast and prior to conducting the diffusion coefficient test. Following the standard procedure, the second measurement was taken on water-saturated samples (>98 % relative humidity). The resistivity values shown are the arithmetic mean of the readings measured in at least two samples of each type of concrete.

4.- RESULTS

The experimental values found for the oxygen diffusion coefficients, porosity and electrical resistivity in the 12 sample materials studied are discussed below.

4.1.- Porosity

The mean porosity values given in Table 3 show that, as expected, the concretes with less cement, a higher w/c ratio and shorter curing time under humid conditions were more porous.

The tortuous porosity values calculated with Equations [2] and [3] are also listed in the table.

Table 3. Porosity (vol.%) and tortuous porosity* values				
Concrete type (kg/m^3 -W/C- curing)	Porosity, ε (vol. %)	Tortuous porosity, ε^t		
		$\rho_e = \rho_0 \cdot \varepsilon^t$ [2]	$\emptyset = \emptyset_0 \cdot \varepsilon^t$ [3]	
			With $\emptyset = \emptyset_{th}$	With $\emptyset = \emptyset_m$
300-0.55-2 days	13.9	0.0048	0.012	0.136

300-0.55-28 days	6.9	0.0042	0.012	0.075
400-0.41-2 days	8.7	0.0047	0.010	0.085
400-0.41-28 days	6.4	0.0042	0.014	0.203

* calculated from Equations [2] and [3]

4.2.- Diffusion coefficients

Further to the diffusion cell findings given in Table 4, the diffusion coefficients lay within the range reported in the literature (10^{-7} m²/s to 10^{-8} m²/s)²⁰. Those results were likewise consistent with expected behaviour, with higher values observed for concrete with shorter curing times and lower cement contents. RH content was also found to affect the diffusion coefficient, which tended to be lower at higher RH.

Table 4. Oxygen diffusion coefficient values (m²/s)

Concrete type (kg/m ³ -W/C- curing)	Relative humidity		
	50 %	75 %	84 %
300-0.55-2 days	1.95×10^{-7}	1.70×10^{-7}	1.75×10^{-7}
300-0.55-28 days	4.85×10^{-8}	4.80×10^{-8}	1.33×10^{-8}
400-0.41-2 days	1.02×10^{-7}	1.05×10^{-7}	1.09×10^{-7}
400-0.41-28 days	4.05×10^{-8}	4.00×10^{-8}	1.00×10^{-8}

Figures 3, 4 and 5 reveal a qualitative correlation between the diffusion coefficient (Table 4) and porosity (Table 3), according to which the more porous the material, the higher its diffusion coefficient.

Figure 3. Porosity (%) versus diffusion coefficient (m²/s) at 50 % relative humidity

Figure 4. Porosity (%) versus diffusion coefficient (m^2/s) at 75 % relative humidity

Figure 5. Porosity (%) versus diffusion coefficient (m^2/s) at 84 % relative humidity

Conversely, the lower the tortuous porosity, the higher was the diffusion coefficient. By way of example, tortuous porosity (Table 3) as calculated from Equation [3] ($\emptyset = \emptyset_0 \cdot \epsilon^{-\tau}$, with $\emptyset = \emptyset_m$), and the diffusion coefficient (m^2/s) (Table 4) are graphed in Figure 6 for 84 % relative humidity.

Figure 6. Tortuous porosity ($\bar{\epsilon} = \epsilon_0 \cdot \epsilon^{-\tau}$, with $\epsilon = \epsilon_m$), versus diffusion coefficient (m^2/s) at 84 % relative humidity

4.3.- Electrical resistivity

The mean electrical resistivity values for water-saturated specimens observed immediately prior to the diffusion coefficient test are listed in Table 5. Here also the results were consistent with expected behaviour, with lower values observed for concrete with shorter curing times and lower cement contents. The inverse correlation between resistivity and porosity is clearly visible in Figure 7.

Table 5. Electrical resistivity values ($\Omega \cdot \text{cm}$) in water-saturated specimens

Concrete type (kg/m^3 -W/C-curing)	Resistivity ($\Omega \cdot \text{cm}$)
300-0.55-2 days	10 249
300-0.55-28 days	11 839
400-0.41-2 days	10 514
400-0.41-28 days	11 928

Figure 7. Porosity (%) versus electrical resistivity ($\Omega \cdot \text{cm}$).

5.- DISCUSSION

5.1 Qualitative correlation between diffusion coefficient, porosity and electrical resistivity

To date, it has not been possible to find the oxygen or gas diffusion coefficient in concrete directly from the microstructural parameters of the material, even though relating the two parameters would simplify the assessment of two gas transport-associated properties: carbonation resistance and airtightness.

This study aimed to find an expression to calculate the oxygen diffusion coefficient (D_{O_2}) for ordinary portland cement concrete from Equation [1] using other, more readily found empirical parameters such as concrete porosity (ϵ), tortuous porosity (ϵ^*) and electrical resistivity (ρ_e), as measured in the OPC concretes described in section 3.1.

Even at first glance the findings (exemplified in Figure 8) revealed a qualitative correlation among the parameters (higher resistivity and lower diffusion coefficients in less porous materials), confirming the feasibility of a mathematical relationship. Less porous materials have fewer voids in the concrete matrix, which hampers both air/gas diffusion (lower coefficient) and water penetration (higher resistance to ion travel).

Figure 8. Diffusion coefficients (for three RH values) and resistivity versus porosity and tortuous porosity (from $\emptyset = \emptyset_0 \cdot \epsilon^{-\tau}$, with $\emptyset = \emptyset_m$)

5.2 Value of n

Equation [1] above, where n is a constant dependent on the concentration of the external aggressive agent, has been used to define the relationship between the diffusion coefficient and resistivity in electrolytes, in which ion travel can be likened to that of electrical charges. The feasibility of applying Equation [1] to model gas transport was explored in this study, assuming that, although gas molecules are not electrically charged, their mobility can be quantified and modelled in much the same way as the components of electrolytes.

Quantifying parameter n in Equation [1] is critical to any attempt to establish a quantitative relationship between the diffusion coefficient and resistivity. Once it is found, D_{O_2} can be calculated directly from resistivity.

The experimental values for resistivity and the diffusion coefficient in the four types of concrete (mix-curing condition combinations) were applied to determine n for each RH with Equation [1] (Figure 9). Contrary to electrolytes where n is constant, here it varied from 1 to 20 depending on concrete composition and curing time (the two parameters with the greatest effect on concrete porosity). At any given RH, n tended to grow with concrete porosity, for diffusivity was higher and resistivity lower in the more porous materials. The less significant effect of relative humidity may have been due to its measurement in water-saturated specimens in all cases.

Figure 9. n values obtained by substituting experimental D_{O_2} and ρ_e values into Equation [1]

5.3 Relationships between n and concrete parameters

The n values found for the 12 sample materials by entering the experimental resistivity and diffusion coefficient values into Equation [1] were plotted against the parameters associated with concrete microstructure: porosity (ϵ) and tortuous porosity (ϵ^T). The analyses performed for concrete porosity (ϵ) and for tortuous porosity (ϵ^T) (using Equation [2]) are represented by way of example in Figure 10.

Calculations were performed to establish both linear and non-linear relationships with n as the independent variable.

Figure 10. n versus porosity (left) and tortuous porosity (right, from $\rho_e = \rho_0 \cdot \epsilon^T$)

The linear regression equations calculated for ϵ (Figure 10, left) were:

- a) For 50 % RH: $n = 200.80 \cdot \epsilon - 7.82$ at $R^2 = 0.98$
- b) For 75 % RH: $n = 200.71 \cdot \epsilon - 9.83$ at $R^2 = 0.87$
- c) For 84 % RH: $n = 221.97 \cdot \epsilon - 12.01$ at $R^2 = 0.88$

The nearly identical slope and y-intercept values for all three RH values denoted a highly robust relationship for that parameter. Porosity and electrical resistivity values are independent of RH, because they were measured with dry and saturated samples respectively, so the only variable parameter is diffusion coefficient, varying depending on the RH.

The non-linear regression equations for ϵ delivered fits comparable to those of the linear models, although the expressions themselves differed with the RH values:

- a) For 50 % RH: $n = 20 \ln(\epsilon) + 59.35$ at $R^2 = 0.99$

- b) For 75 % RH: $n=780.65 \cdot \varepsilon^{1.83}$ at $R^2=0.96$
c) For 84 % RH: $n=-4827.7\varepsilon^2+1225.5 \varepsilon-58.98$ at $R^2=0.96$

The linear regression equations calculated for ε^τ (Figure 10, right) were:

- a) For 50 % RH: $n=17871 \cdot \varepsilon^\tau-70.36$ at $R^2=0.82$
b) For 75 % RH: $n=20203 \cdot \varepsilon^\tau-82.90$ at $R^2=0.93$
c) For 84 % RH: $n=22648 \cdot \varepsilon^\tau-94.20$ at $R^2=0.96$

Here also the slopes and y-intercepts were similar.

The linear regression equations for the ε^τ values derived from Equation [3] (see Table 3) yielded poorer fits, with the non-linear regressions delivering less favourable fits than the linear expressions for that parameter.

The scant effect of tortuosity on parameter n might be attributed to the fact that gas molecules may be less likely than the ions in the pore solution to interact with pore walls.

In light of the aforementioned findings and since ε is more readily determined than ε^τ , the results for the latter were not taken into any further consideration.

The regression expression delivering the best fit (conveniently for 50 % RH, the easiest condition to establish) was as follows:

$$n=20 \ln(\varepsilon)+59.35 \quad R^2=0.99 \quad [7]$$

That expression could be used to estimate the n value in Equation [1] directly from overall concrete porosity.

5.4 Diffusion coefficient vs porosity and vs electrical resistivity: quantitative correlations

Applying the foregoing, the oxygen diffusion coefficient, D_{O_2} , can be calculated from resistivity by substituting the n value estimated with equation [7] into Equation [1], rewritten as:

$$D_{O_2} = \frac{20 \ln(\varepsilon)+59.35}{\rho_e} \quad [8]$$

Using Equation [8], the diffusion coefficient for OPC concrete can be estimated directly from experimental resistivity (ρ_e), provided porosity (ε) is known and lies within the range studied. The values found with Equation [8] are compared to the experimental findings on the oxygen diffusion coefficient-porosity plot in Figure 11. In Figure 12, the coefficient is graphed against electrical resistivity for four porosity values.

Figure 11. Diffusion coefficient vs porosity, experimental and calculated values

Figure 12. Diffusion coefficient vs electrical resistivity for four overall porosity values, calculated with Equation [8]

Further research would be needed to determine whether these equations can be used with concretes made with other than OPC or exhibiting a different range of porosities. The expectation is that they should be applicable, inasmuch as they depend exclusively on empirical porosity values.

6.- PRACTICAL APPLICATION

Given that in practice the easier a method the better, the linear regression equation for 50 % RH could be used:

$$D_{O_2} = \frac{200.80 \cdot \epsilon - 7.82}{\rho_e} \quad [9]$$

In the absence of porosity values and assuming 50 % RH conditioning, the following highly simplified expression could be applied:

$$D_{O_2} = \frac{10}{\rho_e} \quad [10]$$

7.- CONCLUSIONS

The conclusions that can be drawn from this study of diffusion coefficient - overall porosity - electrical resistivity relationships in OPC concretes are set out below.

1. In OPC concretes with overall porosity ranging from 6.4 % to 13.9 %, the diffusion coefficient is related to electrical resistivity as described by the following equation:

$$D_{O_2} = \frac{20 \cdot \ln(\varepsilon) + 59.35}{\rho_e}$$

2. With that equation the oxygen diffusion coefficient can be estimated directly from experimentally convenient parameters such as porosity, measured as in ASTM-D4404-18, and electrical resistivity, as in EN 83988-1.
3. This equation is proposed for ordinary portland cement concrete only. Nonetheless, as it is based on porosity, which can be determined for any concrete, it may possibly be applicable as well to materials made from other types of binders.
4. Where porosity lies within the range specified, other more simplified equations might also be used, such as:

$$D_{O_2} = \frac{200.80 \cdot \varepsilon - 7.82}{\rho_e}$$

8.- ACKNOWLEDGEMENTS

The assistance provided by José María Alonso Polvorosa in conducting the MIP measurements is gratefully acknowledged.

9. FUNDING

This study was funded exclusively by the three authors' employer, the Spanish National Research Council.

10.- CONFLICTS OF INTEREST

The authors declare no conflict of interest.

11.- REFERENCES

-
- ¹ E. Medina, Construcción de estructuras de hormigón armado. Delta publicaciones. 2ª edición. Universidad Politécnica de Madrid (2007) ISBN 84-96477-96-7.
 - ² J. Kropp et al., Transport mechanisms and definitions. Performance criteria for concrete durability. RILEM REPORT 12 (1995).
 - ³ S. Darby et al., Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. [on line]. <<http://www.bmj.com/content/330/7485/223>>. [Consulted: 16-06-2015].

-
- ⁴ C. Sáinz and L.S. Quindós, Comparative risk or assessment of residential radon exposures in two radon-prone areas, Stei (Romania) and Torrelodones (Spain). *Science of the Total Environment*, 407 (2009) p. 4452-4460.
- ⁵ P. Linares et al., Advances in characterization of gas transport in concrete: Determination of oxygen diffusion coefficient from permeability coefficient and porosity. Service life and durability of reinforced concrete structures. Selected papers of the 8th International RILEM PhD Workshop held in Marne-la-Vallée, France, September 26-27, 2016. RILEM Bookseries, 17 (2018) ISBN 978-3-319-90235-7.
- ⁶ AENOR. Concrete durability. Test methods. Determination to gas permeability of hardened concrete. UNE 83981: 2008. Madrid.
- ⁷ RILEM TC 116-PCD. Permeability of concrete as a criterion of its durability. Final report: Concrete durability – An approach towards performance testing. *Materials and structures*, 217 (1999) p. 163-173.
- ⁸ C. Andrade, Types of models of service life of reinforcement: The case of the resistivity. *Concrete research letters*, vol. 1, 2 (2010) p. 73-80.
- ⁹ C. Andrade, Calculation of chloride diffusion coefficients in concrete from ionic migration measurements. *Cement and concrete research*, 23 (1993) p. 724-742.
- ¹⁰ E.J. Garboczi, Permeability, diffusivity and microstructural parameters: A critical review. *Cement and concrete research*, Vol. 20. No. 4 (1990) p. 591-601.
- ¹¹ C. Andrade et al., Calculation of tortuosity factor for the model based in concrete resistivity. Second international conference on microstructural-related durability of cementitious composites, 11-13 April 2012, Amsterdam, The Netherlands.
- ¹² Y.F. Houst and F.H. Wittmann, Influence of porosity and water content on the diffusivity of CO₂ and O₂ through hydrated cement paste. *Cement and concrete research*, 24 (1994) p. 1165-1176.
- ¹³ K. Kobayashi and K. Shuttoh, Oxygen diffusivity of various cementitious materials. *Cement and Concrete Research*, Vol. 21, 2–3 (1991) p. 273-284.
- ¹⁴ L.J. Parrott, Moisture conditioning and transport properties of concrete test specimens. *Materials and Structures* 27 (1994) p. 460-468.
- ¹⁵ S.H. Jung, M.K. Lee, B.H. Oh, Measurement device and characteristics of diffusion coefficient of carbon dioxide in concrete. *ACI Mater J* 108 (6) p. 589-595.
- ¹⁶ European Committee for Standardization. Concrete durability - test methods - conditioning of concrete test pieces for the purpose of gas permeability and capillary suction tests. EN 83966: 2008.
- ¹⁷ European Committee for Standardization. Concrete durability - tests methods - determination of the electrical resistivity. Part 1: direct test (reference method). EN 83988-1: 2008.
- ¹⁸ ASTM. Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry. ASTM D4404-18.
- ¹⁹ ISO/DTS 11665-13 Measurement of radioactivity in the environment – Air: radon 222 – Part 13: Determination of the diffusion coefficient in waterproof materials: membrane two-side activity concentration measurement method.
- ²⁰ Gaber, K. Influence of mix proportions and components on the diffusion coefficient and the permeability of concrete. *Darmstadt Concrete*, 3 (1988) p. 39-48.