

Non-destructive Electrical Methods for Measuring the Physical Characteristics of Porous Materials

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Abstract The durability of reinforced concrete structures, built on the seafront, has been at the heart of recent concerns. Indeed, chloride transport across the porosity of concrete coating produces medium to long-term corrosion of reinforcements. This has a direct impact on the mechanical behavior and the ageing of the affected structures. The difficulty of in situ monitoring of these structures, continuously and non-destructively against infiltration of chlorides, is still topical. The work presented here aims mainly at correlating the electrical properties, i.e. electrical resistance, conductivity..., with the physical characteristics (porosity, tortuosity, ...), of granular materials using Archie's law. The recommended experimental program consists in placing, different granular materials, i.e. sand, mortar, bricks, and concretes saturated with electrolytic solutions, in a PVC cell fitted with a pair of stainless steel electrodes connected to an electrical circuit, in order to measure the electrical resistances. The results obtained allow one to determine durability factors, such as the connected porosity and the coefficient of chloride diffusion through a simple measurement of the EC, and estimate the tortuosity parameter that governs transport in porous media.

Keywords Concrete · Non-destructive testing · Chloride · Granular material · Porosity

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1 Introduction

Reinforced concrete structures, close to the coast, are often degraded due to the infiltration of chlorides within the concrete coating; thus inducing reinforcement corrosion and causing subsequent pathologies. This major deterioration mechanism renders the costs, associated with the repair and maintenance of damaged structures, excessive. Indeed, controlling the state of these structures has become an essential step in their lifetime. For these reasons, non-destructive examination methods are increasingly used to evaluate their resistance and durability within aggressive environments.

Non-destructive methods are used to examine objects, equipment or systems without harming their proper operation. The role of these monitoring techniques is to follow the evolution of a few parameters in space and time. Among these methods, it is worth noting ultrasounds, dynamic, electromagnetic, electric methods, etc.

Electrical measurements are easy to use in situ, fast, reliable and especially not expensive. Given these attractive features, a large number of applications have been developed for electrical measurements in various domains of science and engineering.

Two key parameters of these electrical methods are the electrical conductivity (EC) and its reciprocal, the electrical resistivity, which are often used as indicators for assessing the amplitude of known parameters such as porosity, permeability, saturation, diffusion coefficient, etc. In a fully saturated porous system, the electrical conductivity is mainly ionic because the particles themselves are small electrical conductors, [1–3] the current passes mainly through interstitial water.

Numerous works, known today, are based on the measurement of the electrical conductivity or the electrical resistivity,

whether for soils or cementitious materials. It is well known that many parameters, such as the composition of the interstitial fluid and its concentration, porosity, saturation level, mineralogy (dimension and shape of the particles), the internal structure (pore distribution, pore shape and degree of cementing) and temperature, may affect the EC of a saturated system [4–17].

The EC is measured in order to assess the concentration of chlorides in the coating of reinforced concrete structures [18,19]. However it's used to monitor corrosion of reinforcement and quantify the critical threshold of chloride concentration charge of the initiation of corrosion on reinforced concrete [12,20–22]. It's also used to control the quality and strength of concrete [13,23]. The stability of self-placing concretes was quantified, in this way [16]. The hydration process of cements at early age could be followed using the (EC) [24]. Control the effect of temperatures on concrete including freeze–thaw cycles and better understand the impact of this phenomenon on the degradation of reinforced concrete structures was studied using this electrical parameter [25]. Assessed the salinity and the productivity rate of soils was succeeded by this method [3,26]. Certain transport parameters, i.e. permeability or diffusion coefficient were able to be determined [27–30]. The electrical impedance can also be used in quantification of the physical properties of porous materials as monitor the microstructural characteristics of cementitious materials at early age [31]. Electrical resistivity represents the inverse of conductivity and remains an important parameter used in many recent studies, indeed it's Used for the measurement of alkali content and their influence on the microstructure and transport properties in the cementitious materials [32]. In another way electrical resistivity or electrical resistance were used to study the fissures and discontinuities (concrete joints, interfaces ...) in reinforced concrete on damaged structure [33,34]. Finally, the effect of the concentrations of the salts on the electrical resistivity in cements treated clays, correlating it with the cement parameters stabilized with salt-rich soil [35].

The majority of these works were carried out in laboratories where everything was controlled, using sophisticated experimental tools and technical measures that were only partially reproduced in situ.

The main objective of this work is to use a very simple electrical measurement system, not expensive, easy to implement, either in the laboratory or on site. This non-destructive technique of measurement was used to evaluate physical parameters, such as porosity, tortuosity or diffusion coefficient. For this purpose, several porous materials, such as glass beads, sand, brick and cementitious materials were placed in PVC cells fitted with a device to measure the EC, and saturated with a saline solution at various concentrations.

2 Theoretical Aspect of the Electrical Properties of Materials

2.1 Relation Between the Electrical Conductivity EC and the Porosity ϕ

Most granular materials are poor conductors, except the oxides, metal sulphides, and graphite. Therefore, conduction within rocks is mainly electrolytic; this is due to the presence of water inside pores. Obviously, the nature of the fluid plays an important role; the higher the salt concentration of water is, the more conductive it becomes.

There are several models relating the porosity and the EC, initially developed for sedimentary rocks, but can still be applied to all types of rocks and other cementitious materials [36–39]. The conduction relationship within porous materials is described by Archie's empirical law (1942). In the case of a fully saturated material, Archie's formula can be written in a more simplified [3,40]

$$\frac{EC}{EC_0} = \frac{1}{F} = \phi^m \quad (1)$$

where EC is the apparent electrical conductivity, EC_0 the electrical conductivity of water inside the pores, F the formation factor which represent the lumped effect of the microstructure on the electrical conductivity of the material, it's the ration of the pore solution conductivity and the apparent electrical conductivity, ϕ the porosity of the medium and m cementation or porosity exponent called Archie's exponent, which varies with the porous material (Table 1).

Katz and Thompson suggested model which also relies porosity with electrical conductivity equation (2), showing that it can be predicted from the mercury intrusion measurement [41,42]. The expression is as follows:

$$\frac{1}{F} = \frac{d_{max}^e}{d_c} \phi S(d_{max}^e) \quad (2)$$

- d_{max}^e : The electrical conductivity characteristic dimension that produces max. conductance, ($d_{max}^e = 0.34d_c$ for a very broad pore size distribution),
- d_c : critical pore diameter (nm),
- $S(d_{max}^e)$: Fractional volume of connected pore space involving pore widths of size d_{max}^e and larger,

It is clear that Eq. (1) is no longer valid if rocks contain clay. Indeed, the presence of clay in a porous rock contributes significantly to increase its electrical conductivity, as it helps also to increase the ion concentration in the aqueous phase [43].

For cementitious materials, another form of Archie's law is typically expressed in terms of the electrical resistivity.

Table 1 Archie’s exponent (m) for some porous media, published in the literature [3, 10, 44, 45]

| Porous media | Porosity | m^a | Reference |
|--------------|-----------|------------|----------------------------|
| Glass beads | 0.38–0.40 | 1.35 | Friedman and Robinson [10] |
| | 0.37–0.40 | 1.38 | |
| | 0.33–0.37 | 1.20 | |
| Quartz sand | 0.40–0.44 | 1.45 | Friedman and Robinson [10] |
| Rocks | | 1.3 à 2.5 | Naar [44] |
| Concrete | ≤ 0.2 | 3.5 to 4.6 | Naar [44] |

^aArchie factor

This form highlights the relationship that exists between the electrical resistivity ρ of the porous material, the resistivity of the electrolytic solution ρ_0 , the saturation level S ($S = 1$ for a fully saturated material) and the porosity ϕ :

$$\rho = a\rho_0\phi^{-m}S^n \tag{3}$$

a lithology parameter, n saturation exponent, m cementation or porosity exponent called Archie’s exponent. Subsequent studies proved the variation and the choice of these parameters for the validity of Archie’s law for concretes [44].

2.2 Tortuosity

The tortuosity τ_m is a geometrical factor which represents the distance crossed by the diffused interstitial solution through a porous medium. It is generally expressed as follows [46–48]

$$\tau_m = \left(\frac{L}{L_e}\right)^2 \tag{4}$$

where L is a straight-line, the macroscopic distance between two points defining the flow path, and L_e is the microscopic real or effective distance, traveled by the electrolytic solution through soil between the same two points. Since $L_e > L$ for porous media, then $\tau_m < 1$. The values of τ_m range from 0.01 to 0.84 for saturated soils, and from 0.025 to 0.57 for unsaturated soils [49]. In some cases, the tortuosity factor is defined as the reciprocal of Eq. (3) and, therefore, will have a value greater than one [48, 50, 51].

2.3 Diffusion

Diffusion is a fundamental irreversible process, in which matter is spontaneously transported from one part of a system to another, resulting from random molecular motion [52, 53] Diffusion is described as the net transport of a chemical species from a region with a higher concentration to a region with a lower concentration, due to a concentration gradient of the chemical species.

$$\frac{\partial C}{\partial t} = D^* \frac{\partial^2 C}{\partial x^2} \tag{5}$$

There is a model which relies porosity, tortuosity factor T_m and constrictivity δ with apparent coefficient diffusion D_i [54–56]:

$$D_i = \frac{D_0\delta\phi}{T_m} \tag{6}$$

Knowing that $\tau_m = \left(\frac{L}{L_e}\right)^2 = \frac{1}{T_m}$

The constrictivity can’t be determinate independently but approached to 1 [57] And so the term $\delta/T_m < 1$ represents τ_m

Equation 6 can be written as:

$$D_i = \theta_w \tau_m D_0 \tag{7}$$

$$\theta_w = \phi Sr$$

In case on fully saturated media $Sr = 1$ so $\theta_w = \phi$.

Where ϕ is porosity, (D_0) is the self-diffusion coefficient of solute in the pore fluid of the porous media, τ_m is known as the geometric tortuosity factor.

It is noted that the effective diffusion coefficient: D^* is the D_i/ϕ

So the effective diffusion coefficient D^* of a chemical species in a porous medium, is defined as the product of the free diffusion coefficient D_0 of the same chemical species in liquid phase and the tortuosity as follows [58]:

$$D^* = D_0 \cdot \tau_m \tag{8}$$

Equation (5) is the most common form of Fick’s second law, governing the one-dimensional transient diffusion of chemical species in an aqueous solution. D^* is the effective diffusion coefficient, C the concentration of chlorides in the solution of soil present in the porous medium, t the time, and x the depth. The initial conditions in this case are:

$C(x \leq 0, t = 0) = C_0$; $C(x > 0, t = 0) = 0$; $C(x = \infty, t > 0) = 0$. [53], Eq. (5) has a solution of the form:

$$\frac{C}{C_0} = \text{Erfc} \left(\frac{x}{2(D^*t)^{1/2}} \right) \tag{9}$$

Table 2 Properties of materials used

| Material | Granular class (mm) | Formulation | Ratio W/C | Density | EC (S/m) |
|-----------------|---|-----------------|-----------|---------|----------|
| Glass beads | (1.5 or 2 or 3 or 4) | – | – | 2.53 | 0 |
| Sand | [(0.25 – 0.5) or (0.5–1) or (1–2)] | – | – | 1.6 | 0 |
| Sand-lime brick | – | – | – | 1.9 | 0 |
| Red brick | – | – | – | 1.96 | 0 |
| Mortar | Sand (0–4) | 1/3 | 0.5 | 2 | 0 |
| Concrete | Sand (0–4) + gravel (4–8) + gravel (8–16) + gravel (16–25) | BO ^a | 0.5 | 2.3 | 0 |

ECGs electrical conductivity of solid particles

^aBoukli Hacene [67]

where C_0 (constant) is the concentration of the non-reactive solute in the source reservoir, C the concentration at time t and position x , and $Erfc$ the complementary error function.

3 Materials and Methods

3.1 Materials Used

Several materials were used in this experimental program. Their characteristics are summarized in Table 2.

3.2 Measurement Method

The procedure of measuring the material's conductivity in samples is based on the equivalent form of Ohm's law for AC currents:

$$V = Z \cdot I \quad (10)$$

Z is a complex number composed of real and imaginary components; $Z = Z' + jZ''$.

The real part of impedance (Z') is called resistance, while the imaginary part (Z'') is called reactance.

In most porous media at frequency below 100 KHz $Z' = R$, $Z'' = 0$ [29,59,60] and the impedance became is independent of frequency and is governed by ohmic conduction (R).

And then the conductivity of sample can be calculated with Eq. (11):

$$CE = L/R \cdot A \quad (11)$$

L is the distance (meter) between the two electrodes, and A the area of the electrodes (m^2).

3.3 Cell Characteristics

The cell is an HDPE cylinder with a diameter of 50 mm and a height of 50 mm, equipped with two stainless steel

electrodes of dimensions (30 × 50 mm), similar to the one used in literature [15,29,61] set at mid-height of the cell and connected by electric cables to the measuring device (Fig. 2).

3.4 Influence of the Current Frequency

The impact of the electrical frequency was investigated in order to determine the appropriate frequency range for our test. With the two-electrode method, there is an effect of electrode polarization, usually for very low frequencies. It's explained that in soils, this mechanism occurs at frequencies lower than 2 or 3 kHz. Disturbances may also interfere at high frequencies [59]. According to literature the electrical conduction is independent of frequencies between 500 and 500 KHz [15,29,60].

3.5 Porosity Measurement

The measurement of porosity was conducted using two methods: a direct one based on volumetric ratios and an indirect one that uses the electrical method.

3.5.1 Direct Porosity Measurement

For the materials used, i.e. glass beads, sand, etc..., the test consisted in determining the porosity for each granular class, using Eq. (12), which represents the empty volume V_v out of the total volume V_c . The volume of solid grains V_s had to be determined. For this purpose, 50 g of glass beads were poured into a graduated cylinder containing 50 ml of water. The volume difference represents the volume of solid grains V_s , and the total volume V_c represents the volume of the cell.

$$\phi = V_v/V_c \quad (12)$$

With $V_v = V_c - V_s$

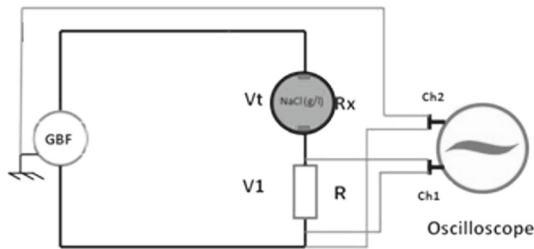


Fig. 1 Electrical circuit used

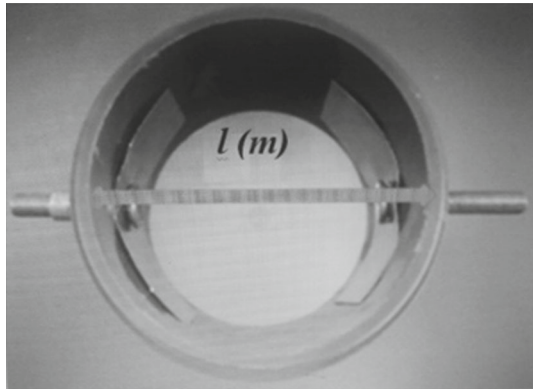


Fig. 2 Cell used for the electrical measurement

For the other materials, i.e. bricks, mortar, concrete ..., vacuum saturation tests were adopted, according to the standard recommended by (AFPC-AFREM modified).

3.5.2 Indirect Porosity Measurement

The indirect method consists in measuring with our circuit (Fig. 1), the electrical resistance of a cell (Fig. 2), filled to the rim with particles constituting the porous medium (glass beads, sand) and saturated with saline solutions at different concentrations of NaCl (0–117) g/l.

Coring on a sand-lime brick and a red clay brick was performed to retrieve samples with 45 mm diameter, fitted with electrodes for electrical measurement. For mortar and concrete, cells with 110 mm of diameter were used. Saturation was done using a vacuum pump (AFPC-AFREM modified) with NaCl salt solutions (0–117) g/l.

3.6 Relation Between the Electrical Conduction and the Concentration of Media

In this section we tried to find the relationship between the EC and the concentration of different types of materials (sand, glass beads, bricks, mortar and concrete) with porosities ranging from 44.2 to 13.4 %.

For sand and glass beads, the samples were placed in a cell (Fig. 2), after drying in an oven at 105 °C. Saturation with saline solutions (NaCl) with values 5, 10, 20, 29.5, 58.5 and

117 g/l was obtained by filling the cell with the corresponding solution.

With regards to the sand-lime brick and the red clay brick, samples of 45 mm of diameter were cored in the bricks, and were then equipped with electrodes for electrical measurement. The test specimens of mortar and concrete were cast into cells 110 mm of diameter, equipped with electrodes, after a cure of 28 days and drying at 65 °C, until the mass stabilized. These materials were saturated with NaCl solutions at different concentrations, using a vacuum pump (AFPC-AFREM modified). Electrical conductivity (EC) measurements were performed for all materials, for each concentration, using our electrical circuit (Fig. 1).

3.7 Tortuosity Measurement

Tortuosity is another very important factor that affects the transport and diffusion of chlorides through porous media. Equation (13a) represents the Nernst–Einstein equation which can be used for a non reacting ionic species to relate diffusion and ionic conductivity [61,62]:

$$\frac{D_i}{D_0} = \frac{EC}{EC_0} \tag{13a}$$

From Eqs. (7) and (13a) we can deduce:

$$\frac{EC}{EC_0} = \tau_m \phi \tag{13b}$$

where EC is the electrical conductivity of the porous medium, τ_m the tortuosity, ϕ the porosity, EC_0 the electrical conductivity of the solution, measured with a conductimeter. The measurement of the electrical conductivity for the materials used was carried out by the electrical method (Fig. 1) previously described, but that of EC_0 was done with a digital conductimeter (OHAUS-STARTER 3000C).

On the other hand from Eqs. (1) and (13b) we can express the geometric tortuosity factor with the porosity of the saturated porous media as:

$$\tau_m = \phi^{(m-1)} \tag{14}$$

Equation (14) will apply only in fully saturated porous media which using on the first form of Archie law, i.e. it is no longer valid when it is cementitious materials.

3.8 Diffusion Test

Several diffusion tests were performed. The first ones consisted in monitoring the diffusion evolution of a saline solution of NaCl (29.5 g/l) in distilled water (Fig. 3a). The cell consisted of a PVC part of 45 mm of diameter, which contained distilled water with two electrodes placed on another

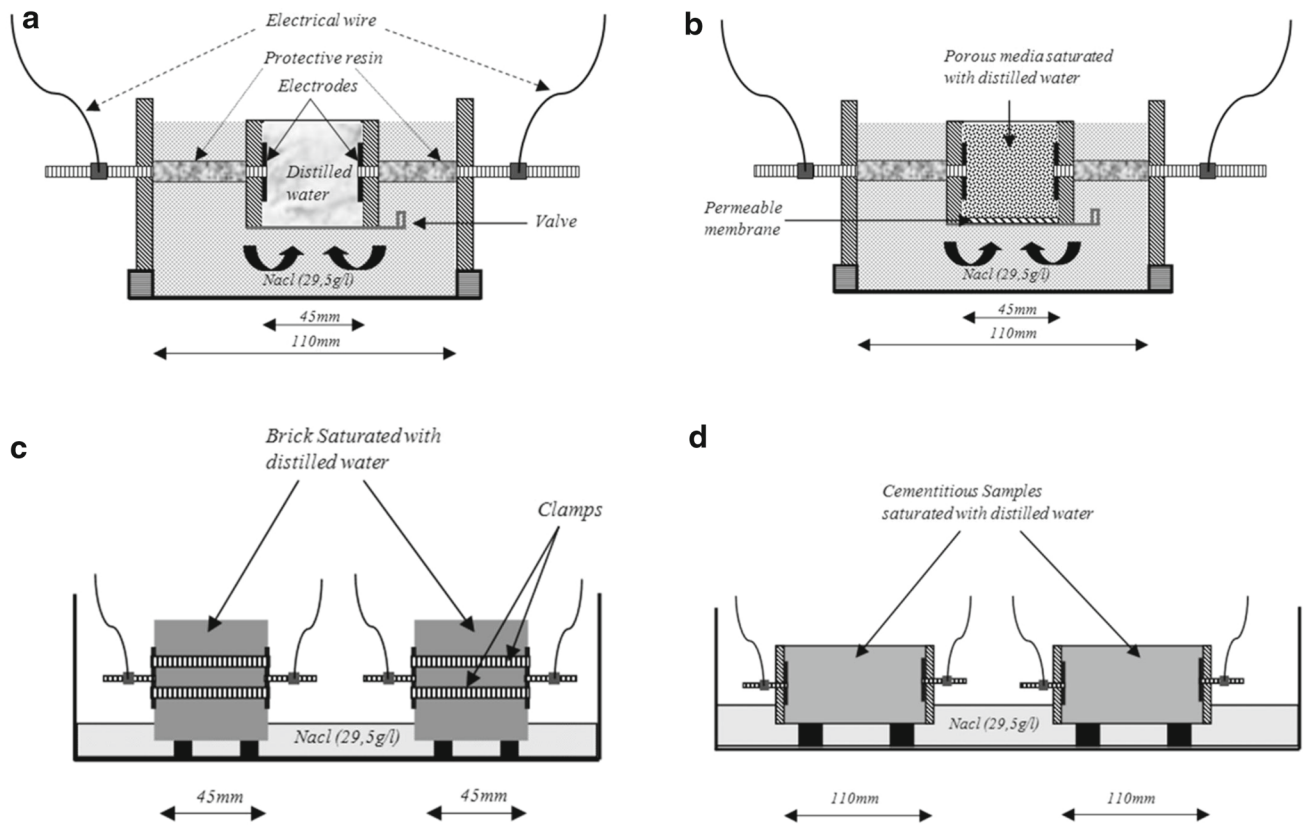


Fig. 3 (a) Cell of free diffusion for saline solution (29.5 g/l). (b) Cell diffusion for glass beads and sands. (c) Diffusion tests for bricks. (d) Diffusion tests for cementitious materials

cell of 110 mm of diameter, containing the saline solution. The same cell was used for glass beads and sand, and a permeable membrane was placed at the bottom of the inner part to retain the porous materials (Fig. 3b). Those materials were saturated with distilled water and the outside cell was filled with the diffusive NaCl solution (29.5 g/l).

Cores of 45 mm of diameter were equipped with stainless steel electrodes; clamps were used to ensure good contact between the core and the electrodes. These samples were placed in a reservoir containing the diffusing NaCl solution (29.5 g/l).

Figure 3d represents the diffusion tests carried out on cementitious materials. Mortar samples were cast into cells of 110 mm in diameter and 50 mm in height, equipped with two electrodes. With regard to concrete, specimens were realized into (11 × 22) cm PVC cells, equipped with electrodes. The heart of the sample was used to perform the test. Both materials were saturated with distilled water with a vacuum pump as recommended by (PSAC AFREM modified), placed in a reservoir containing the diffusing solution (NaCl at 29 g/l).

The electrical measurements for all materials were carried out using the electrical circuit (Fig. 1), every hour for the first day, and then every 24 h.

4 Results and Interpretations

4.1 Influence of the Frequency

A great number of the tests performed on our materials, saturated with NaCl at different concentrations, allowed us to note the influence of the frequency on the EC. Figure 4 is an example, among the tests realized, where glass beads of

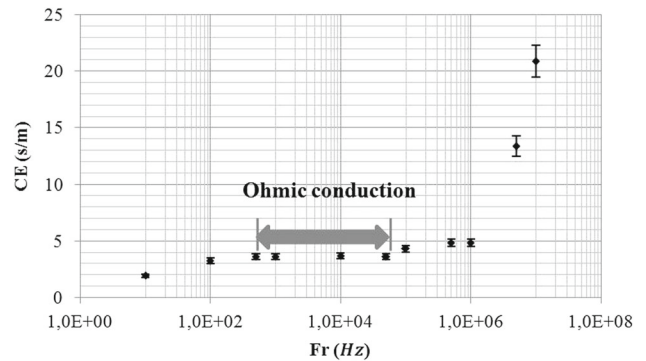


Fig. 4 Variation of the electrical conduction with the frequency, for glass beads of 4 mm in diameter, saturated with NaCl at a concentration of 117 g/l

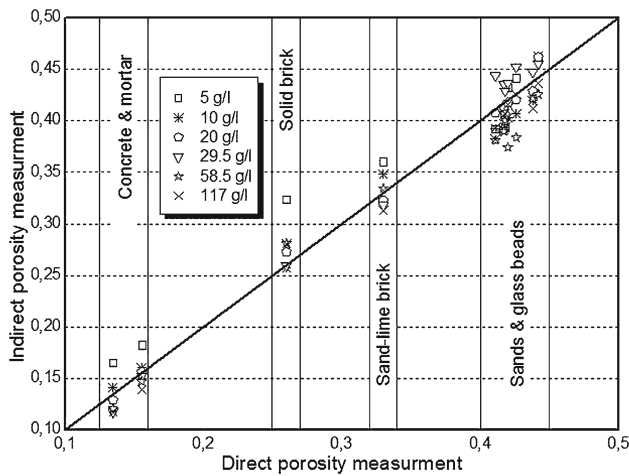


Fig. 5 Relation between porosity values measured by direct and indirect methods

4 mm in diameter, saturated with NaCl (117g/l) are used. It is noted that the electrical conductivity increases with the frequency and stabilizes on a certain level, and then continues to rise exponentially. The same tendency was observed in many works [15,29,60]. This level is the ohmic conduction, where Ohm’s law is valid and totally independent of the frequency. Consequently, it is worth retaining that the range of appropriate frequencies for our tests is in the interval (500–50 KHz).

4.2 Porosity

In Fig. 5, the x-axis represents the porosities found by the direct method, the y-axis the porosities determined by the electrical method. Each point on the figure represents the average of three tests.

It is noted that the values given by the two methods are close for porosities higher than 0.33, for all concentrations. On the other hand, for materials having porosities lower than 0.33, indirect porosity values are found close, for concentrations higher than 5 g/l. Porosity results are similar to those found in the literature; it is $0.37 \leq \phi \leq 0.45$ for glass beads and $0.39 \leq \phi \leq 0.47$ for sands [10]. The porosities of bricks are 0.33 for the sand-lime brick and 0.26 for the red brick [63], for concrete and mortar, it is 0.134 and 0.156, respectively [64–67].

The indirect porosity was obtained using the classical Archie’s law equation (1) by varying the adjustment factor m in order to have indirect porosity values as close as possible to the direct porosity values. The best results were obtained with $m = 1.45$ for sands, $m = 1.35$ for glass beads, $m = 2.3$ for the sand-lime brick and $m = 2.5$ for the red clay brick. This fits well with the parameters found in literature [3] for different materials ($1.3 < m < 2.5$). However, the use of the same classical law with cementitious materials is not

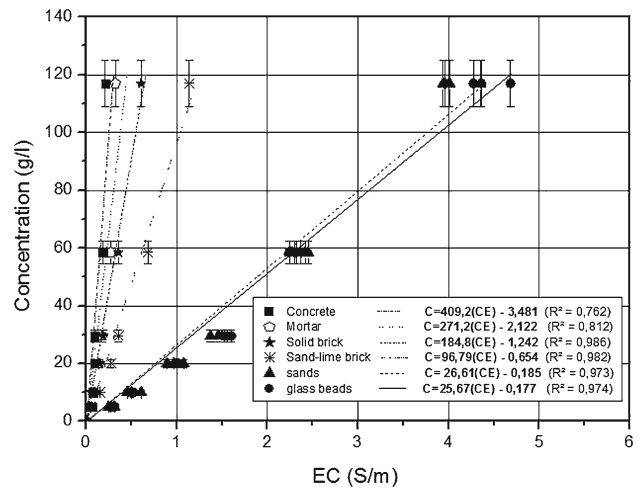


Fig. 6 Relation between NaCl concentration and EC for the materials under study

recommended due to aberrant values found. Another form of Archie’s law is known; it includes other adjustment factors (a, m, n), seen in Eq. (3). The employ of this law for cementitious materials, especially for concretes, was able to be validated [44]. In the case where the resistivity of the fluid varies between 0.03 and 0.27 varies from 0.1 to 0.8 [68] for Concrete $a = 0.028$ [44], and m takes values > 3 , and can go up to 4.6 ($n \approx 2$). In the present study, we took $m = 3$ with $a = 0.1$ for mortar and $m = 3.5$ with $a = 0.028$ for concrete.

4.3 Relation Between the Electrical Conduction (EC) and the Ionic Concentration (NaCl)

Figure 6 shows the EC measured for porous materials saturated with NaCl solutions at various concentrations (0–117 g/l). It is easily observed that for the same material, the higher the concentration, the larger the electrical conduction. However, for two different materials, saturated with the same concentration, EC was higher in the more porous material.

The relationship obtained for each material had a typical linear trend in the form $(ax - b)$. It was noted that the parameters a and b vary with the porosity; they actually increased as the porosity decreased. This relationship allows one to correlate the porosity and the two parameters (a, b), through an equation of exponential type with regression factors ≥ 0.949 . Therefore, for a material with porosity between 0.134 and 0.442, saturated with NaCl solution, whose concentration ranges between 0 and 117 g/l, the relation between the concentration and the electrical conduction of the porous medium may be written as follows:

$$C = 1444 \cdot e^{-9.01\phi} (EC) - 12.52 \cdot e^{-9.64\phi} \tag{15}$$

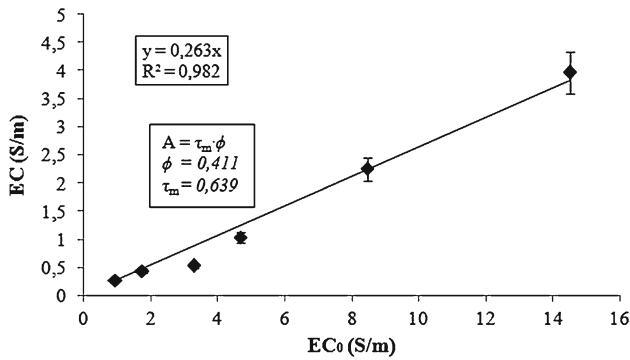


Fig. 7 Tortuosity calculated with the Eq. (13b)

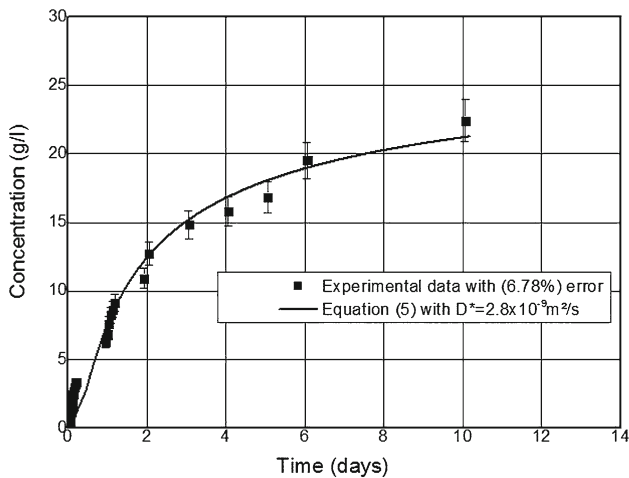


Fig. 8 Diffusion concentration profile of NaCl solution (29.5 g/l)

4.4 Totusosity

Figure 7 shows the variation of EC as a function of EC_0 in glass beads 1.5 mm in diameter, saturated with a solution of NaCl at a concentration between 0 and 117 g/l. This variation was found in the form of a straight line with a correlation coefficient of 0.98 and a slope equal to $\phi \cdot \tau_m$ with porosity equal to 0.411. Therefore, tortuosity is equal to 0.683.

Table 3 shows the values of tortuosity determined using Eq. (13b). It is noted that the tortuosity varies with the nature of the medium and therefore changes with the geometrical properties of the porous media.

4.5 Diffusion

The values measured for the free diffusion of NaCl solution (29.5 g/l) are shown in Fig. 8 as a cloud of points. A rapid increase of chlorides was noted during the first hours, followed by a relatively slow evolution over a trial period of 10 days. Adjustment with Eq. (9) allowed deducing the diffusion coefficient D_0 , found equal to $2.8 \times 10^{-9} \text{ m}^2/\text{s}$ [49]. Error bars defines uncertainties on the electrical measure-

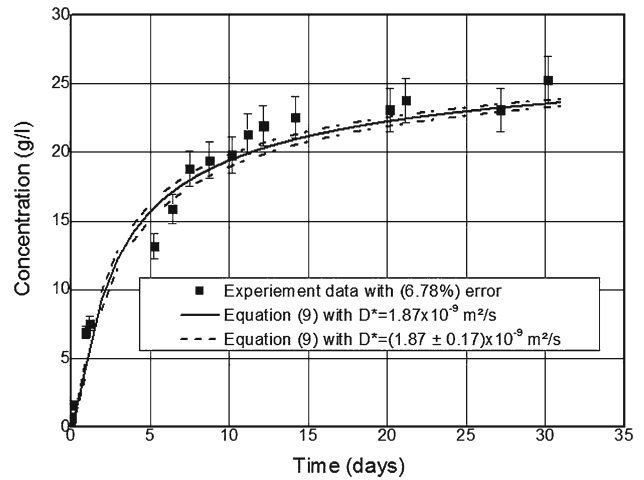


Fig. 9 Diffusion concentration profile in sand (1–2 mm)

ments made with the electrical circuit (Fig. 1) and estimated to be 6.78 %. The model is seen to be inside this surface and adjusts well to this result.

For sand of class (1–2) mm (Fig. 9) and glass beads of diameters 1.5 and 2 mm (Fig. 10a, b), the adjustment using the model of Eq. (9) helped deduce, respectively, for sand of class (1–2) mm and glass beads of (1.5, and 2) mm, the effective diffusion coefficients $D^*(1.87 \cdot 10^{-9}, 1.78 \cdot 10^{-9}, 1.91 \cdot 10^{-9}) \text{ m}^2/\text{s}$, calculated with the tortuosities given in Table 3, using Eq. (8). Knowing that the tortuosity is also electrically measured, it also contains an error estimated at 9.32 %, and the error on the diffusion coefficient is approximately $(\pm 0.18 \cdot 10^{-9} \text{ m}^2/\text{s})$. Diffusion coefficients and their errors adjust well with the experimental results.

With regard to diffusion in sand-lime and red bricks (Fig. 11a, b), a very good concordance was observed between the experimental values and the adjustment model adopted according to Eq. (9). The effective diffusion coefficients are $(6.44 \pm 0.59 \cdot 10^{-10}) \text{ m}^2/\text{s}$ and $(3.98 \pm 0.37 \cdot 10^{-10}) \text{ m}^2/\text{s}$, for the sand-lime brick and the red brick, respectively. The results obtained in literature [69] for bricks were found to be of the order of $(4.5 \times 10^{-10}) \text{ m}^2/\text{s}$; they are close to our results.

Tests performed on cementitious materials (mortar and concrete) lasted more than six months, and no change was ever detected, when using our electrical circuit (Fig. 12). This may be explained by the magnitude of the diffusion coefficient of concrete, which is of the order of $10^{-12} \text{ m}^2/\text{s}$ [70,71]. The time needed to detect a concentration greater than 5 g/l with such an order of magnitude Of D^* , easily exceeds 12 months.

The main results of tortuosity and diffusion coefficients obtained for our materials are summarized in Table 4. The diffusion tests performed allow one to see that the effective diffusion coefficients D^* of the studied media are less than the diffusion coefficient D_0 of the free diffusion of a saline solution alone. This is due to the tortuosity of the medium studied,

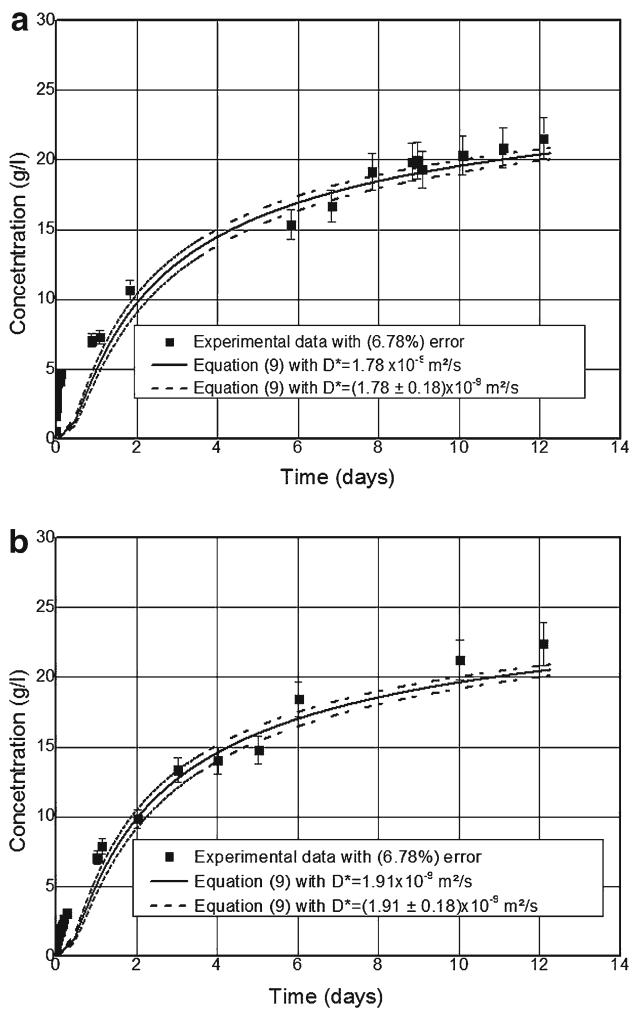


Fig. 10 a Diffusion concentration profile in glass beads (1.5 mm). b Diffusion concentration profile in glass beads (2 mm)

Table 3 Tortuosity measured on different materials

| Material | Tortuosity | Porosity |
|--------------------|------------|----------|
| Glass beads 2 mm | 0.685 | 0.417 |
| Glass beads 1.5 mm | 0.639 | 0.411 |
| Sand (1–2) mm | 0.671 | 0.442 |
| Sand-lime brick | 0.230 | 0.33 |
| Red clay brick | 0.142 | 0.26 |
| Mortar | 0.121 | 0.156 |
| Concrete | 0.08 | 0.134 |

and it can therefore be deduced that the diffusion performed for the studied materials obeys Eq. (8). Table 4 shows that the tortuosity parameter varies with the nature of the porous medium. This change also affects the effective diffusion coefficient which, indeed, decreases as tortuosity goes down.

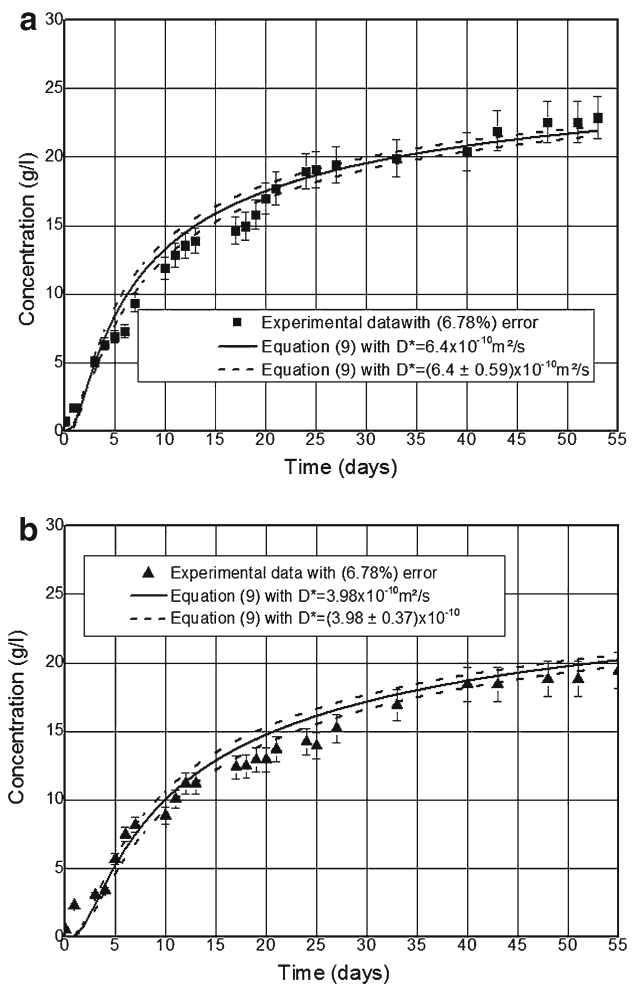


Fig. 11 a Diffusion concentration profile in a sand-lime brick b Diffusion concentration profile in a red clay brick

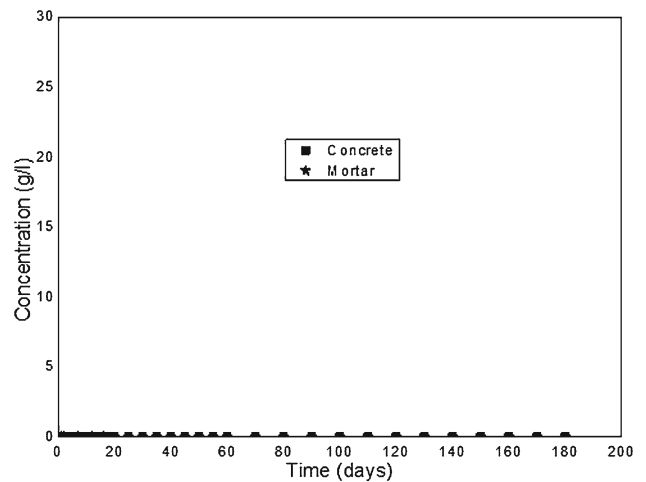


Fig. 12 Diffusion concentration profile in cementitious materials

Table 4 Influence of tortuosity on the effective diffusion coefficient

| Materials | Tortuosity | Diffusion coefficient |
|--------------------|-------------------|----------------------------|
| Glass beads 2 mm | 0.685 ± 0.064 | $(1.91 \pm 0.18) 10^{-9}$ |
| Glass beads 1.5 mm | 0.639 ± 0.060 | $(1.78 \pm 0.18) 10^{-9}$ |
| Sand (1–2) mm | 0.671 ± 0.062 | $(1.87 \pm 0.17) 10^{-9}$ |
| Sand-lime brick | 0.230 ± 0.021 | $(6.44 \pm 0.59) 10^{-10}$ |
| Red clay brick | 0.142 ± 0.013 | $(3.98 \pm 0.37) 10^{-10}$ |

5 Conclusion

The use of a simple and effective nondestructive electrical method was investigated in this work. The influence of the electrical frequency was observed, and the field of appropriate frequencies for the used electrical circuit was found in the interval (500 Hz–50 KHz). The electrical measurements performed made it possible to correlate perfectly the electrical parameters with the physical properties in the porous media studied.

A strong correlation was noted between the electrical conductivity (EC) and the porosity of granular materials tested, where the most important values were found for media with high porosity. Moreover, EC measurements for several porous materials with porosity between 13.4 and 44.2, saturated with a NaCl saline solution, with a concentration ranging from 0 to 117 g/l, allowed establishing an exponential relationship between the chloride concentration and the EC , and therefore concluding that it is actually possible to estimate, at any time, the proportion of NaCl chlorine ions in a porous medium, through a simple electrical measurement. It was also possible to develop a diffusion cell that enables measuring the concentration evolution in a solution or in a porous medium.

An important step in this work was the evaluation of the diffusion coefficient. Indeed, a multitude of tests allowed confirming the efficiency of the method chosen in determining durability factors, such as porosity and diffusion coefficient through tortuosity. A simple measurement of EC can inform one about that durability indicator.

This work also permitted to see the influence of tortuosity on the diffusion phenomenon. The higher the tortuosity, the faster the diffusion is; this offers a higher diffusion coefficient.

Several issues remain to be seen for the continuity of this work, mainly the effectiveness of the circuit in the determination of the diffusion coefficient for cementitious materials; this requires a monitoring period of more than 12 months for EC . Finally, using this non-destructive technique in the in situ auscultation of concrete structures located in aggressive environments, still needs to be validated.

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