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Influence of the age on air permeability of concrete

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A great interest is being taken in the measurement of concrete permeability because of increased concerns about the durability of concrete when exposed to aggressive environments. However, the variation of the concrete permeability with time has not been systematically studied. Air permeability results recorded for 20 years in six 0.2 m^3 concrete slabs are presented. These results have a qualitative value as boundary effects are unknown. The great difference in flow between the specimens with the same mix design, casting and curing procedure, which have been kept in the same testing room sheltered from rain, is noticeable. The air permeability coefficient increases with time, reaching an almost stable value after 20 years. The pore evaporated water creates a path for air flow through the concrete and this is supposed to be the main cause of the increase in permeability. The method presented in this paper gives reliable information about the quality of the concrete studied in terms of air permeability and hence, durability.

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1. Introduction

The long-term performance of concrete is at present a topic of great interest. This has led to increased study of the parameters related to its durability and the testing methods for its determination as in the case of air permeability. Concrete structures are designed to ensure acceptable limits of deformation and ultimate strength values, and for a long time the compressive strength has been considered the only indicator for durability. Currently, control of durability is being realized by means of requirements of minimum values of strength, cover thickness, time of curing and restrictions of constituents and mix proportions [1]. However, these parameters are not completely valid for ensuring the long-term performance of the concrete because they neither take into account the chemical and physical changes of the concrete due to the penetration of aggressive external agents nor the influence on the rate of intrusion of these agents. Therefore, studies of other properties of the concrete related to its permeability have to be considered.

The permeation characteristic of concrete is one of the most important factors affecting the servicelife of a concrete structure. The relationship between permeability and porosity of hardened cement pastes has been discussed in the literature [2–5]. Depending on the pore structure, the environmental agents could penetrate more or less easily. Permeability in cement pastes appears to depend mainly on pores that have diameters greater than 0.132 μm [3], even though the shape and interconnection also play a leading role. For instance, the pastes of blended cements have a lower permeability than those of Portland cements, although they show a greater porosity [6]. This seems to be a consequence of the blocking of the narrow connecting pores by means of dissolution, transport and precipitation phenomena [7]. Apart from the porosity of the cement paste in the concrete, it is also necessary to take into account the presence of aggregates, which are sometimes not randomly distributed, and the transition zone between these and the cement paste.

Summing up, it can be deduced that a direct correlation between porosity and permeability in concrete remains uncertain and, therefore, the direct measurement of the permeability is nowadays the most reliable method of assessing this property. In particular, the permeability of the concrete cover to CO_2, air (oxygen), chlorides and water is critical for problems related to corrosion of reinforced concretes, while for bulk concrete air permeability is especially important, for nuclear containment vessel applications, for example.

Several types of fluids have been used to measure concrete permeability: water, salt solutions, oils, air, oxygen, carbon dioxide, water vapour, and so on [8–10]. The disadvantage of water and water solutions lies in the possible reaction with the solid, reducing the actual permeability. On the other hand, gas permeability tests strongly depend on the moisture content of the sample, and therefore, the concrete is usually preconditioned. This process involves prior drying of the specimen; the manner in which this operation is performed has an appreciable effect on

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the outcome of the tests [6, 11]. Thus, measuring permeability with gases is more delicate than testing using water as a permeable fluid.

The microstructure of the concrete may be altered during the preconditioning process producing microcracking and damage of the C–S–H sheets when it is subjected to an energetic drying. Various preconditioning methods have been proposed to avoid extreme drying such as solvent replacement or freeze drying, for instance [12]. The differences in permeability due to the type of treatment are ascribed to the transformation of the fine-pore structure into a coarser one due to the tensile stresses resulting from the water meniscus [6, 13]. Besides, cracks can be induced, thereby promoting an increase in the permeability coefficient. Since reinforced concrete structures kept in a natural environment, not immersed in water, at least partly undergo drying, microcracks will form in the cement matrix and will contribute, together with the capillary pores, to determine the concrete permeability. Microcracking is also induced by the action of external forces [14] and heating gradients [15]. A drying conditioning that does not induce crack formation can only be obtained under controlled laboratory conditions. It is therefore necessary for technical applications to know how the concrete will behave under actual conditions, that is, its ability to crack. For the moment, only a few studies have been carried out on the air permeability of microcracked concrete [16].

In the present work, an air permeability test procedure is presented as a reliable method to assess the durability of the concrete. This is because of its relationship with the microstructure, and hence relates to the ingress of aggressive external agents. The objective of this paper is to demonstrate the importance of the ageing of the concrete on the air permeability as a consequence of the internal changes of moisture and microstructure, forming gradients from the surface layer to the bulk concrete. The significance of the research presented in this paper lies in the systematic study over 20 years (1965–1985) of air permeability measurements and the reliability of the testing method for technical applications.

2. Experimental procedure

2.1. Materials

An ordinary Portland cement P-350 was used whose average chemical characteristics are given in Table I. All the materials employed followed the Spanish Standard PCCH-64 [17].

2.2. Mix design

Six slabs with a water/cement ratio of 0.37 were made with the mix design shown in Table II. The dimensions were $200 \times 1000 \times 1000\ \mathrm{mm^3}$. This means that $0.2\ \mathrm{m^3}$ of concrete were placed in each mould. The casting was done in two layers and the mass was vibrated with a poker vibrator working at 9000 r.p.m.. The specimens were cast in moulds made of steel (passing sides) and wood (lateral sides and bottom).

TABLE I Chemical characteristics of a P-350 cement

C_3A	MgO	SO_3	Loss of ignition	Insoluble residue
< 18%	< 5%	< 4%	< 4%	< 3%

TABLE II Concrete dosage

Material	Gravel	Stone	Sand	Cement	Water
Amount ($\mathrm{kg\,m^{-3}}$)	387	871	651	405	150

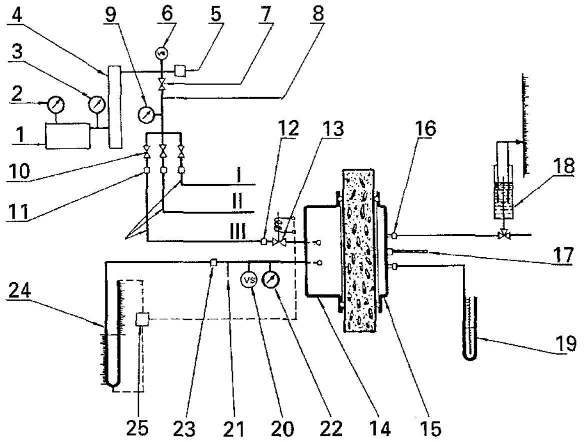

Figure 1 Air permeability apparatus: (1) compressor of $10\ \mathrm{kg\,cm^{-2}}$ of maximum pressure; (2) and (3) metallic manometers of $8\ \mathrm{kg\,cm^{-2}}$; (4) compressed air reservoir; (5) pressure gauge "Billman" type PD38 (ΔP from 3 to $8\ \mathrm{kg\,cm^{-2}}$); (6) safety valve set at $4\ \mathrm{kg\,cm^{-2}}$; (7) 1/2 inch intake valve; (8) relief valve; (9) metallic manometer of $5\ \mathrm{kg\,cm^{-2}}$; (10) 1/2 inch intake valves; (11) connecting nuts 3/8 inch SAE; (12) connecting nut 1/2 inch SAE; (13) solenoid check valve "DANFOSS" type EVJ 10–220 V; (14) inlet pressurized air cell; (15) outlet air cell; (16) connecting nut 3/8 inch SAE; (17) mercury thermometer; (18) Cylinder with a piston containing the outflow (50 cm height and 12 cm diameter); (19) manometer U-type; (20) safety valve (set at $2.5\ \mathrm{kg\,cm^{-2}}$); (21) relief valve; (22) metallic manometer of $3\ \mathrm{kg\,cm^{-2}}$; (23) connecting nuts 3/8 inch SAE; (24) manometer U-type; (25) Electrical control system of inlet air pressure.

The 28 days compressive strength was about 40 MPa in Ø15 × 30 cm cylindrical specimens. The specimens were placed in a test room of $33 \times 13 \times 7\ \mathrm{m^3}$ which was sheltered from rain. The hydrothermal conditions of relative humidity and temperature ranged between 40–70%, and 15–25 °C, respectively.

2.3. Testing procedure

An experimental device was designed to measure air permeability in concretes. Fig. 1 shows schematically the equipment used. The device is composed of two metallic cells placed at each side of the specimen. In the first one having 150 l capacity, inlet air is held at the chosen pressure by means of a compressor and a precision pressure regulator. In the second one of 10 l capacity, the passing air is measured at atmospheric pressure in a cylinder with a piston in which the outflow is collected. The air flow rate is measured under steady-state conditions. The two metallic cells were designed to resist 50 MPa. They were screwed to the specimens closed by bolts and using rubber O-ring seal joints, leaving a circular passing surface of 0.353 m^2 on both sides.

The air flow rate was corrected by Equation (1), in order to remove the effects of increasing kinematic viscosity and volume expansion of air with rising temperature.

2.4. Air permeability coefficient calculation

The rate at which a fluid passes through concrete is in inverse ratio to the viscosity of the fluid; consequently, when passing from water to air the permeability coefficient increases considerably. The air flow, Q, obtained at the environmental pressure, P, and temperature, T, were transformed to normal conditions, Q_0, of pressure, P_0, and temperature, T_0, using Equation 1.

$$Q_0 = \frac{T_0}{T}\frac{P}{P_0} \tag{1}$$

The air permeability coefficient, D_{air}, was calculated according to the Hagen–Poiseuille equation for a laminar flow under steady-state conditions of a compressible fluid through a porous material composed of a network of small capillary pores (Equation 2).

$$D_{\text{air}} = \frac{2QP_0L\eta}{A(P^2 - P_a^2)}\,[\text{m}^2] \tag{2}$$

where Q = air flow ($\text{m}^3\,\text{s}^{-1}$), A = passing area (m^2), L = specimens thickness (m), η = dynamic viscosity ($\text{N}\,\text{s}\,\text{m}^{-2}$), P = absolute inlet pressure ($\text{N}\,\text{m}^{-2}$), P_a = absolute outlet pressure ($\text{N}\,\text{m}^{-2}$), and P_0 = pressure at the measuring gas-meter ($\text{N}\,\text{m}^{-2}$).

The air at 20 °C has a value of dynamic viscosity of $1.8 \times 10^{-5}\,\text{N}\,\text{s}\,\text{m}^{-2}$. The inlet pressures in the test, P, were 140 553, 194 491, 233 620 and 287 658 $\text{N}\,\text{m}^{-2}$, and the outlet and measuring pressure, P_a and P_0, respectively, were equal to atmospheric pressure. The circular passing surface, A, was 0.353 m^2 and the specimen thickness, L, was 0.2 m. Substituting these values in Equation 2, the air permeability coefficient can be easily calculated for each pressure:

$$D_{\text{air}_{(0.14\text{MPa})}} = 2.18 \times 10^{-10} Q_{0.14\text{MPa}}\,\text{m}^2 \tag{3}$$

$$D_{\text{air}_{(0.19\text{MPa})}} = 7.50 \times 10^{-11} Q_{0.19\text{MPa}}\,\text{m}^2 \tag{4}$$

$$D_{\text{air}_{(0.23\text{MPa})}} = 4.66 \times 10^{-11} Q_{0.23\text{MPa}}\,\text{m}^2 \tag{5}$$

$$D_{\text{air}_{(0.28\text{MPa})}} = 2.85 \times 10^{-11} Q_{0.28\text{MPa}}\,\text{m}^2 \tag{6}$$

2.5. Influence of the pressure and temperature correction

The error of a non-corrected measurement has been calculated in order to highlight the importance of the pressure and temperature correction. With this aim, the ideal gas equation is considered (Equation 7).

$$\frac{P \times V}{T} = n \times R = \text{Constant} \tag{7}$$

Differentiating and calculating the finite increments Equation 8 is obtained.

$$\frac{\Delta V}{V} = \frac{\Delta T}{T} - \frac{\Delta P}{P} \tag{8}$$

Then, substituting the working values of volume, pressure and temperature of 0.01 m^3, 710 mmHg and 293 K, respectively, and assuming variations of pressure and temperature of 1 torr and 1 °C, the error resulting from not considering those variations would be:

$$\varepsilon = 100 \times \frac{\Delta V}{V} = \left(\frac{1}{293} \pm \frac{1}{710}\right) \times 100 = 0.2\text{–}0.5\% \tag{9}$$

As the measured volume value ranges between 50 and 500 cm^3, the variation of pressure and temperature in one unit means an error which is of the same order of magnitude as the measurement according to Equation 10.

$$\frac{\Delta V}{V} \times 100 = 0.5\text{–}5\% \tag{10}$$

3. Results and discussion

Fig. 2 shows the time-dependent changes of air permeability coefficient of concrete under the four testing inlet pressures. The plotted values have been obtained from the average of six samples. The degree of dispersion in the results was calculated by means of the coefficient of variation for the population of 6 slabs. The average value was about 50%. It is noticeable that the coefficient of variation is almost independent of the applied pressure and decreases with time from about 60% during the first 4 years to 40% after 20 years of experimentation. The variability of replicate tests under identical test conditions is quite large since concrete is a very heterogeneous material, and hence, different drying out rates are expected in each concrete. Therefore, the coefficient of variation decreases with time as a consequence of the lesser differences in moisture gradients through the concrete between the various specimens. The average coefficient of variation in permeability tests in concrete found by other authors vary from 30% for oxygen [6] up to more than 50% for water [18]. Therefore, the variability of results must be taken into account.

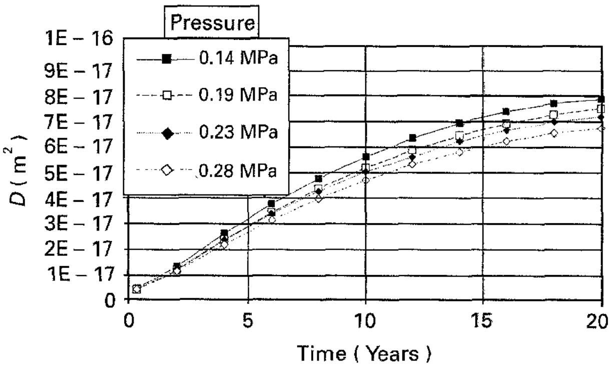

Figure 2 Air permeability coefficient variation over the time.

In the graph shown in Fig. 2 it is possible to clearly distinguish three different regions with time 0–4, 4–12 and 12–20 years. During the first region, several chemical and physical processes occur simultaneously: cement paste hydration, carbonation, drying out and shrinkage of the concrete which induces its microcracking. Hydration and carbonation contribute to reduce the porosity of the material by means of refilling the pores and blocking the interconnected pores with hydration or carbonation products. On the contrary, the drying out of the concrete leads to an easier way for air penetration via: (1) leaving empty channels, and (2) improving the drying shrinkage of the concrete and, consequently, microcracking.

The drying shrinkage and microcracking processes led to a great increase in permeability during the first 4 years of testing. In which the air permeability coefficient, D_{air}, seems to be independent of the applied pressure. The evolution of D_{air} with time has been best-fitted to the rising branch of the function shown in Equation 11. The constants a, b and c for the different pressures used vary from -39 to -40, from 0.61 to 0.63 and from -0.043 to -0.045, respectively ($r^2 > 0.99$).

$$D_{air} = \exp^{(a+bt+ct^2)} \quad (11)$$

The second region is mainly governed by a combination of diffusional processes identified as a straight line in Fig. 3 (e.g. drying out and carbonation of the concrete). This means that the evolution of the D_{air} is linearly dependent on the square-root of the time. The constants A and B in Equation 12 represent all the positive and negative diffusional processes affecting the permeability.

$$D_{air} = D_0 + At^{1/2} - Bt^{1/2} = D_0 + C_i t^{1/2} \quad (12)$$

The entire result is reflected by the C_i constant which is the slope of the straight lines in Fig. 3, corresponding to the second region described above. The coefficients of correlation of those best-fit to a straight line, r^2, were higher than 0.998 in all the cases. The diffusional constants C_i ($i = 0.14, 0.19, 0.23$ and 0.28 MPa) have been calculated for every applied pressure between 2 and 12 years (Table III). The interception of the straight line, D_0, represents the initial air permeability coefficient which should be null due to the complete saturation of the concrete after casting and during the curing period. On the contrary, it is remarkable that the convergence of this value about -2×10^{-17} is independent of the applied pressure.

Finally, the third region can be attributed to a stabilization of the moisture content in the concrete (Fig. 4).

All the experimental data from these three regions have been best-fitted to a quadratic equation of the type: $D_{air} = a + bt + ct^2$. The values of parameters a, b, c and the statistical information are shown in Table IV. It is noticeable that a good correlation in all the cases is obtained even when the first data (0.3 years test) do not follow the general trend.

Fig. 5 shows the relationship between the air flow rate and the applied pressure ratio, P^2–Pa^2. The straight lines in this graph show the good accuracy of the results. A little convex trend of the lines can be observed in Fig. 5 showing the assumption of laminar flow of air through the concrete is not correct in all cases. This dispersion increases with the average permeability of the concrete. The average permeability coefficient, D_{aver}, is obtained from the slope of this straight line. Fig. 6 gives these values obtained with time and the correlation of the best-fit, r^2. From this figure, it can be seen that a good correlation exists in all cases leading to an r^2 value above 0.995.

The air coefficient is a helpful tool for studying this property which should be independent of the applied pressure according to Equation 2. Fig. 7 shows the relationship between the air permeability coefficient and the applied pressure. This figure shows the non-dependence of D_{air} from the applied pressure at the early ages of the concrete. However, with time, there exists an almost linear relationship between D_{air} and the applied pressure ratio $P^2 - Pa^2$.

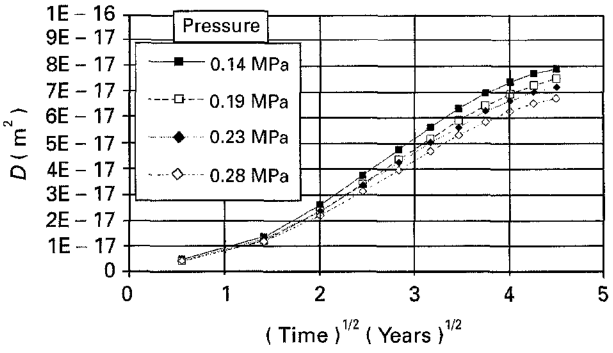

Figure 3 Air permeability coefficient variation with the square-root of the time.

TABLE III The initial air permeability coefficient, D_0, and the permeability constants obtained at different pressures, C_i

Pressure (MPa)	0.14	0.19	0.23	0.28
D_0 ($\times 10^{-17}$m^2)	-2.2	-2.1	-1.8	-1.8
C_i ($\times 10^{-17}$m^{2}yr$^{-0.5}$)	2.47	2.31	2.16	2.05

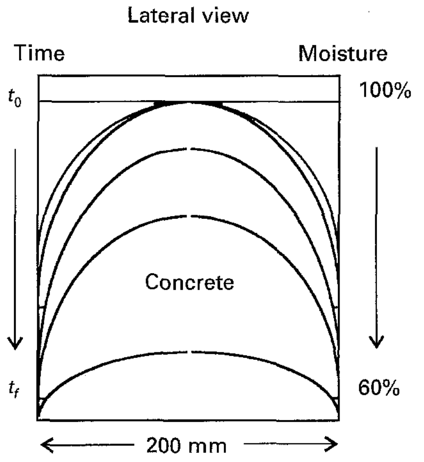

Figure 4 Schema of the internal moisture profile through the concrete from time t_0 to t_f.

TABLE IV Statistical parameters obtained in the best-fit of the experimental data

Parameter	P (MPa)											
	0.14			0.19			0.23			0.28		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
Value ($\times 10^{-20}$)	137	705	− 15	151	617	− 11	181	614	− 13	163	575	− 12
Std error ($\times 10^{-20}$)	61.6	14.3	0.68	76.4	17.8	0.85	38.3	8.89	0.42	41.3	9.61	0.46
t-value	2.22	49.2	− 23	1.98	34.7	− 13	4.72	69.2	− 30	3.96	59.9	− 26
90% confidence limits (lower) ($\times 10^{-20}$)	22	678	− 17	10	584	− 14	109	598	− 14	87	558	− 13
(upper) ($\times 10^{-20}$)	252	732	− 15	294	650	− 10	252	632	− 12	240	593	− 11
r^2 coef. det.		0.9993			0.9988			0.9997			0.9995	
DF adj. r^2		0.9990			0.9983			0.9995			0.9994	
Fit Std. Err ($\times 10^{-20}$)		78.3			97.1			48.6			52.5	
F-value		5572			3396			11739			8882	

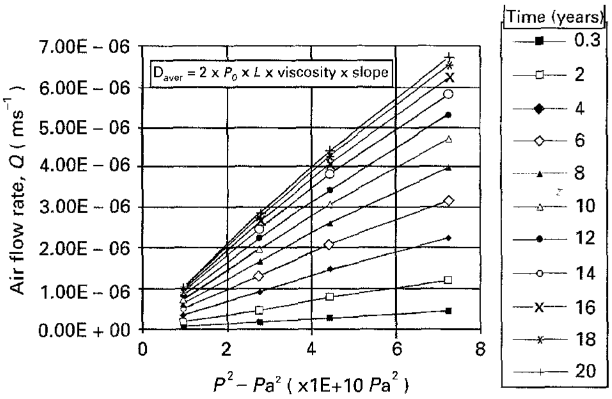

Figure 5 Relationship between the air flow rate and the applied pressure ratio, P^2–Pa^2.

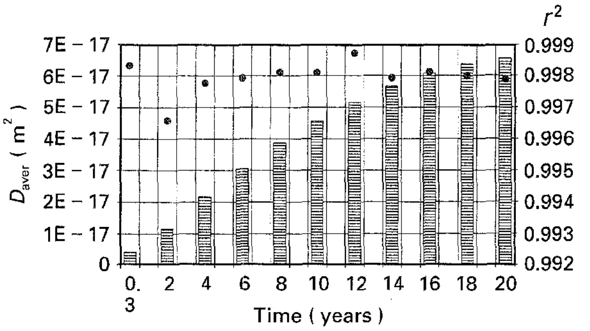

Figure 6 Average permeability coefficient, D_{aver}, obtained over time (bars in the left scale) and the coefficient of correlation of the best-fit, r^2 (points in the right scale).

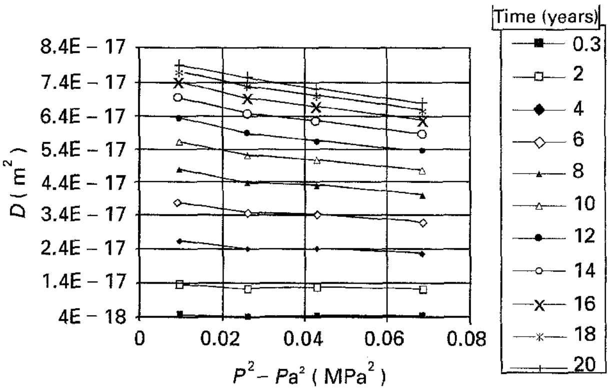

Figure 7 Relationship between the air permeability coefficient, D, and the applied pressure.

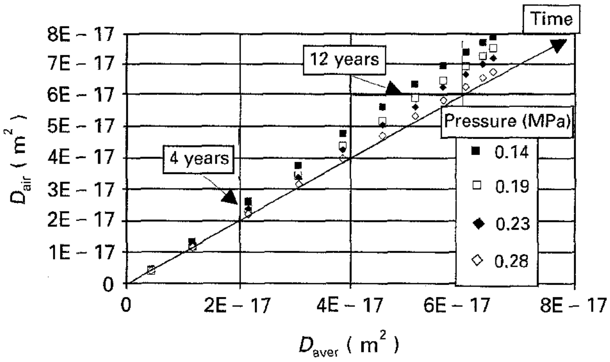

Figure 8 Comparison between the air permeability coefficient calculated from the air flow rate data using Equation 2, D_{air}, and that obtained from the slope of Fig. 5, D_{aver}.

Finally, Fig. 8 compares the air permeability coefficient calculated from the air flow rate data using Equation 2, D_{air}, with the value obtained from the slope of Fig. 5, D_{aver}. It is noticeable the good agreement between the coefficients at all pressures in the young concrete, when the air permeability coefficients are lower. However, there exists a trend of displacement from the equality line in the older concrete, when it is more permeable. Thus, at 0.28 MPa pressures the agreement between D_{air} and D_{aver} is good. On the contrary, at 0.14 MPa pressure, the D_{air} is higher than the correspondent D_{aver}. This means that the D_{air} is a conservative value which could be useful for the design of the concrete mix. The use of high inlet air pressures (approximately 0.23 MPa) is also recommended to obtain more reliable values of D_{air}.

4. Conclusion

Three regions have been identified in the evolution of the air permeability of the concrete with time. In the first one, ranged between 0 and 2 years, a good agreement has been found between the four testing pressures showing the independence of the air permeability coefficient of the pressure. A linear relationship between D_{air} with the square-root of the time has been found between 2 and 12 years, which means a diffusional control, mainly of the internal moisture drying out in the air permeability process, takes place. After this age, this trend is broken down due to a moisture stabilization in the concrete slab.

The method for studying air permeability of concrete gave reliable results with time. It appears that large differences in calculated air permeability coefficient have been obtained for different samples taken from the same batch of concrete under fixed test conditions. Therefore, several samples must be tested in order to get accurate results due to the high coefficient of variation obtained in concretes. According to the present work, the use of six samples is proposed.

The use of a pressure about 0.28 MPa is recommended to carry out the air permeability test. With the specimens made for laboratory testing, the effects of cracking and defects in real structures cannot be evaluated. In order to design a durable concrete mix, it is therefore necessary to interpret with caution the preliminary laboratory tests and afterwards to carry out field tests. It is important to use standardized air permeability testing methods in order to enable a comparison of published permeability data for a better understanding of the effect of all the influencing variables on this property.

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