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Influence of the size and frequency of contact transducers on the determination of concrete permeability by ultrasonic velocity and attenuation

A. Mehamdia[1], A.H. Benouis[2]

1. Civil Engineering and hydraulic Department, Civil Engineering and hydraulic laboratory, University 08 Mai 1945, Guelma, Algeria.
2. Civil Engineering and hydraulic Department, Civil Engineering and hydraulic laboratory, University 08 Mai 1945, Guelma, Algeria.

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A Mehamdia
aalimehamdia@hotmail.com
+213661236024

Abstract

In this paper we prospected the possibility of estimating air and water permeability of concretes by indirect UPV and attenuation, this is for the purpose of substituting the destructive permeability tests realized on cores levied on the structure to auscultated by non-destructive tests in-situ. This study showed an increase in permeabilities with the increase in the W/C ratio. The curing in water affects positively the permeabilities and the correlations of indirect UPV with permeability and attenuation with permeability. The increase of both permeabilities in both curing modes shows a decrease in indirect UPV and an increase in attenuation, this is observed by the various transducers used (d', D, D', d). The correlations between indirect UPV, attenuation and permeability are linear. Changes in velocity are more visible in low permeability concretes, but attenuation is more affected by permeable concretes, this is justified by the changes in the microstructure of the concrete with the W/C ratio. Decreasing in the reflection angle of the transducers improves the correlation between indirect UPV, attenuation and permeability. The increase in the diameter of the transducers improves the correlations between UPV and permeability, and has led to a decrease in correlations between attenuation and permeability, it can be explained by the divergence of the reflection angle (λ_D=0.2λ_d). The increase in the frequency affects negatively the quality of the attenuation/permeability correlation and does not have an important influence on the improvement of the velocity/permeability correlation; this requires a more in-depth analysis for the obtained signals and the microstructure of concrete.

1. Introduction

The lifetime of concrete structures is often related to the capacity of concrete to prevent the penetration of aggressive agents (sulphates, chlorides, CO2…) in its porous structure. The aptitude of concrete cover to resist to these external chemical attacks is conditioned by its properties of transfer (porosity, permeability and diffusivity). These physical properties are related to the characteristics of the porous environment (the shape of the pores, distribution of the sizes of the pores and tortuosity). These parameters can be qualified as indicators of durability. It is obvious that transport behaviours are very important in the context of concrete's durability and therefore a number of researchers are studying on various transport mechanisms, in an attempt to enhance the understanding of concrete deterioration process [1]. Permeability is one of the most important characteristics of concrete, particularly for the case of storage structures. In fact, the increase in permeability (to gas and liquid) and porosity of this material is currently accepted as providing a reliable indication of their degradation (at least on a qualitative level) whether it can be of mechanical or physicochemical origins resulting from the cement matrix being attacked by aggressive substances [2-4]. Recent concerns about the long-term performance of concrete leads to interest being focused on parameters which control the durability and methods of test which meaningfully quantify these parameters [5]. The UPV test, one of the oldest methods for characterizing concrete, is based on measuring the amplitude and travel time of an ultrasonic wave pulse over a known path length. The control by ultrasound is important because of its convenience of use and reasonable cost. It can be considered as one of the most promising methods for evaluating concrete structures, once it is possible to examine the homogeneity of the material. By using the analysis of the propagation variations of the ultrasonic velocity and attenuation, it is possible to measure the uniformity of the concrete, examine the homogeneity and also facilitate the diagnosis of defects. Le test UPV permettre l'évaluation continue des conditions du béton pendant toute la durée de vie de la structure [6-9]].

The indirect waves are mechanical waves propagating parallel along the surface of solid materials with an elliptical particle motion, they have a deep penetration into the solid body better than Rayleigh waves which characterize only the first centimeters of the surface of the solid body, so they can give a survey on the physical and hydraulic state better than that of Rayleigh waves. The penetration depth of waves depends on the frequency of the transducers [10-14]. it called attenuation the phenomenon of weakening of the intensity of the signal of waves propagating in an medium attenuating. This weakening is manifested by a decrease in energy of the signal along its path in the attenuating medium, which results in a decrease in the amplitude of the waves [40].

Measurement techniques of velocity and ultrasonic attenuation using contact transducers that are coupled to a sample of material with a liquid coupling agent or a solid connection are widely used in laboratory and field. The proper coupling is necessary to transfer enough energy into the sample. These techniques have the advantage that they can be applied in situations where a large amount of incident wave energy is required or when the material to be characterized is very strongly attenuating (The direct contact avoids the loss of energy by reflection at the first interface) and/or where environmental conditions do not allow another method. A disadvantage may be that the state of coupling between the transducer and the sample is not completely reproducible, which significantly affects the measured attenuation coefficient and can potentially produce a large random error and/or bias in the measurement results. In the contact attenuation measurement techniques, two ultrasonic pulse signals in the time domain are experimentally obtained and the ratio of their spectra is taken to obtain the attenuation spectrum. The influences of the conditions of contact transducer-sample in these two temporally experimentally measured signals are assumed to be common [43]. Several authors work in the contact mode to measure ultrasonic velocity and attenuation in cement-based materials ([12], [34], [39], [40], [42]) Where they studied the relationships between the ultrasonic parameters speed, attenuation and the properties physics porosity, permeability and segregation. Some researchers have developed an immersion technique in which both the sample and the transducers are immersed in a bath filled with water or other liquid used as a coupler. This technique has the advantage that the coupling between the sample and the transducers is perfect and that an exact acoustic reflection at the water-sample interface can be calculated ([44] [48-49]), but these techniques are difficult to apply to field, and the penetration of water during the test cannot be controlled.

This work consists of studying the correlations between the two ultrasound parameters speed and attenuation of indirect wave and permeability in a cementitious matrix material. This is done in order to have the possibility of setting up estimating the permeability in a non-destructive way in order to substitute the destructive permeability tests carried out on cores taken from the concrete structures. And to enrich this study we used four different transducers by varying the diameter and the frequency of sensors, two types of permeability (to air and to water) were measured on six ordinary concrete compositions (varying the W/C ratio) with two conservation modes (in the open air and in water) for each composition.

2. Materials and methods

2.1. *Materials*

The materials used in this investigation are a portland cement compound, CEM II 42.5, produced by Hdjar-Soud cement factory (Department of Skikda northern Algeria), specific surface of Blaine (SSB) (EN 196-6), and specific surface by laser diffraction (SSDL) (NF X11-666), are illustrated in Table 1 and their chemical compositions and physical properties. A crushed limestone sand (0/5mm) and limestone gravel (5/15mm) are from the quarry of Boucelba (Department of Guelma, northern Algeria), the physical characteristics of the aggregates are summarized in Table 2.

In order to obtain various permeability values, ordinary concrete samples were fabricated with different water/cement (w/c) ratios varied from 0.47 to 0.70. All specimens of concrete are subjected to same condition of compacting and to the same system of curing until the date of testing. Table 3 gives the proportions of the various constituents and physical characteristics of those samples.

2.2 *Ultrasonic test*

The characterizing in situ of concrete structures by indirect measures of ultrasonic waves is carried out mainly when access to only one surface is possible, such as (boards, sails, bridges ...). To perform this measurement, place the transmitter and receiver to the same planar face of the element to test. The transmitter remains on the same point, whereas the receiver is moved each time by performing a measurement [10, 15-16]. The test is according to standard EN12504-4(2004) [17]. The apparatus (E49-UPV brand Controls) consists of an electrical pulse generator, a pair of transducers and an electronic timing device for measuring the time interval elapsing between the onset of a pulse generated at the transmitting transducer and the onset of its arrival at the receiving transducer.

Table 1: Chemical compositions and physical properties of cement

Item	Cement
CaO	59-62
SiO_2	22-24
Al_2O_3	5.3-6.0
Fe_2O_3	3.0-4.0
MgO	1.5-1.8
K_2O	<0.9
Na_2O	<0.7
SO_3	1.8 – 2.2
Absolute density	3.16
SSDL (cm^2/g)	6560
SSB (cm^2/g)	3630

Table 2: Physical characteristics of aggregates

	Unit	Gravel	Sand
Fineness modulus	(%)	/	3.51
Apparent density	(kg/m^3)	1.41	1.49
Absolute density	(kg/m^3)	2.47	2.56

Table 3: Mix proportions and properties of concrete

Constituents (kg/m3)	OC1	OC 2	OC 3	OC 4	OC 5	OC 6
W/C	0.47	0.52	0.55	0.60	0.65	0.70
Cement	400	400	400	400	400	400
Water	188	210	220	240	260	280
Sand (0/5)	813	813	813	813	813	813
Gravel (5/15)	946	946	946	946	946	946
Slump (cm)	6	7	9	13	17	25
Strength MPa	34.2	29.4	25.9	21.8	20.4	19.0

The device comprises an electrical pulse generator (UPV-E49 brand Controls) which measures the time interval between the beginning of a pulse generated and the start of its arrival, a pair of transducers, a digital oscilloscope (Tektronix TDS 1012B) for recording the signals and a PC to store and number the signals (Figure 1). A series of measurements is carried out for the different distances of the receiver noting the propagation time and the peak-to-peak amplitude S (t, Xi) of the signal. The velocity of the indirect waves is estimated from the slope of the linear curve presented in (Fig 1.b). The attenuation of the amplitudes is deduced as a function of the propagation distance (Fig. 1.d). The amplitude changes can be attributed directly to the attenuation behavior of the material [45]. The attenuation coefficient α is expressed in dB/m and calculated from the following equation:

$$\alpha = \frac{1}{Xi - Xj}\left[20\log\left(\frac{Si}{Sj}\right) + 10\log\left(\frac{Xi}{Xj}\right)\right] \quad (1)$$

for each pair i, j in the set of i = 1 ....j ....6, then averaged, making it possible to have a reliable and robust estimate of the attenuation for each specimen [38] [40], where S_i and S_j are the amplitude of spectrum X_i , X_j are the measurement steps of the receiver. Preliminary results give negative values that are underestimated. Some loss of energy can be caused by coupling effects and roughness of the specimen surface. Knowing that the coupling can never be identical in all the tests [46] [47], for this reason, and to ensured the reliability of this work we have used a good formwork (Smooth walls) for the realization of beams, which has given us surfaces of good finishing quality (smooth and perfectly parallel), this allows us to use only a thin layer of the coupler. All measurements were performed by the same operator following the same procedure throughout the experimental series, minimizing the random effects. Apart from this, it was ensured that when the sensors were placed on the surface of the specimens and prior to the start of the test, the lowest frequencies were clearly transmitted. This ensures that coupling is appropriate and that all other frequencies used in the test are reliably transmitted. The attenuation values are absolute because no diffraction correction has been performed on the attenuation curves. The choice of a sensor involves several factors for which compromises must be found. The frequency and the size of the sensors vary the angle of enlargement and the size of the near area. The concrete specimens used for the measurements of indirect UPV and attenuation have dimension 15x15x100 cm^3. A total of six indirect measurements were made on each concrete specimen. The receiving transducer was moved away from the transmitting transducer starting from a center-to-center separation of 5 to 95 cm with an increment of 15 cm. A minimum of three test specimens are required to characterize each concrete. The results of indirect UPV and attenuation determined by the transducers used are shown in Table 4.

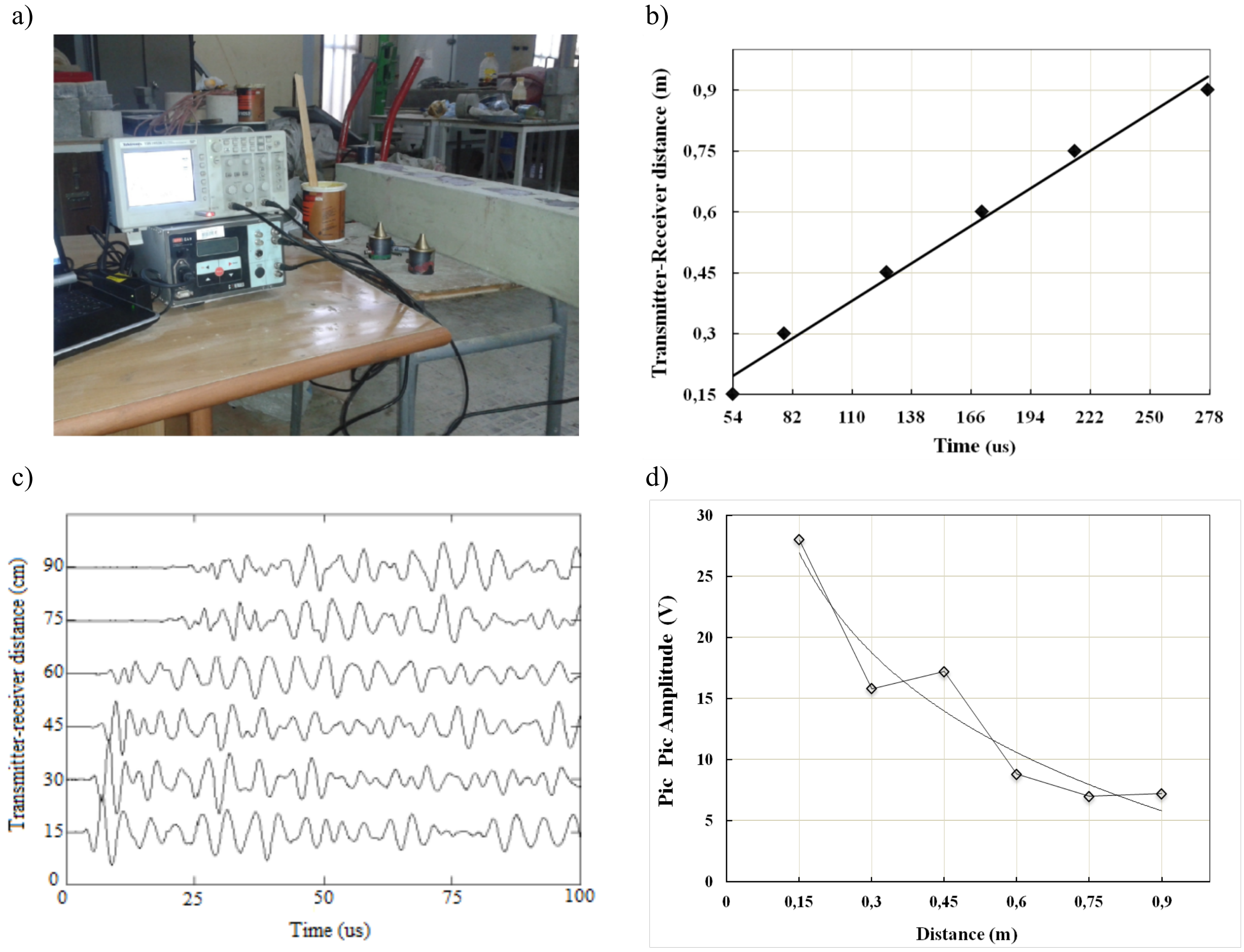

Figure 1: Measurement of indirecte wave velocity and attenuation, a) Experimental device, b) IW velocity estimation using regression, c) Set of six received signals with a constant 15cm increase of the transmitter-receiver distance, d) Determination of attenuation by means of linear interpolation of the IW amplitude

2.3 *Gas permeability*

The general principle of the permeability test is to apply a continuous gas flow through the sample under steady conditions [31]. Apparent permeability is measured using a Cembureau constant head permeameter with pressurized air as the ideal percolating gas. The relative pressure (Pi−Patm) applied to the sample, which ranges between 0 and 0.3 MPa, is read using a pressure gauge [18]. For air permeability tests steady state conditions at three different pressures have been recommended [19]. For concrete samples, can take significant times (varying from 15 min to 60 min). This condition is verified by taking two measurements separated by a 15 minute time interval. If two values differ by less than 2%, the steady state flow condition is assumed to be achieved. The test specimens shall be discs with a thickness of 50 mm ± 1 mm and a diameter of 150 mm ± 1 mm. For each differential pressure, the apparent coefficient of permeability ka (m^2) is calculated from the Hagen-Poiseuille relationship, Equation below, for laminar flow of a compressible viscous fluid through a porous body.

$$K_a = \frac{Q}{A}\frac{2\mu.L.P_{atm}}{\left(P_i^2 - P_{atm}^2\right)} \qquad \left(m^2\right) \tag{2}$$

Where L: thickness of the sample (m), A: cross-sectional area (m^2), Q: measured gas flow (m^3/s), μ: viscosity coefficient ($1.82\ 10^{-5}$ Pa s for air at 20 °C), P_i: inlet pressure, i.e. applied absolute pressure (P_a), P_{atm}: atmospheric pressure (Pa) [6] [20-22].

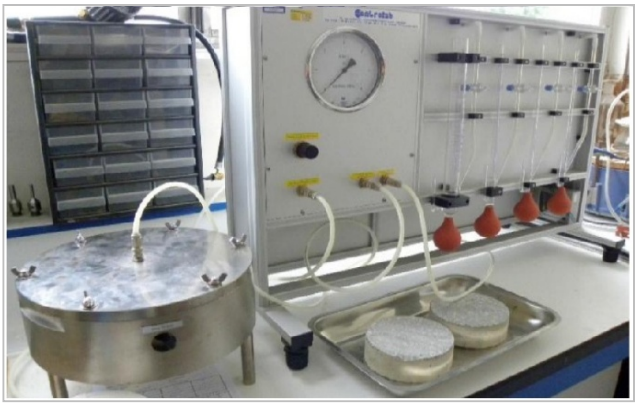

Figure 2: General view of CEMBUREAU gas permeameter

2.4. *Water permeability test procedure (Water Penetration Depth)*
Basic procedure of such a test is to apply water under pressure to one surface of the specimen for a specific time and then split the specimen perpendicular to the injected face and determine visually the depth of penetration h(mm). The test is carried out according to German Standard DIN 1048 on concrete specimens of size 15x15x15 cm3, at an age of 28 days. The test cell assembly being used had the provision for testing three cubes at a time for each type of curing (at air and in water). Once the specimens were assembled in the test cells, a water pressure of 500 ± 50 KPa was applied for 72 hours. Water pressure is applied by means of an arrangement consisting of a water tank connected to an air compressor through a valve, to adjust the pressure [23-25].

Figure 3: Water penetration test setup

2.5. *Curing procedure*
In this study, two curing procedure were followed only on the permeability specimens, curing in open air for 28 days and curing in water for 28 day in tanks. This in order to know the influence of regime curing on the permeability measurement also on the correlation between permeability and indirect ultrasonic pulse velocity. We have performed six permeability specimens for each concrete composition, three for open air curing and three for water curing.

3. Resultats and Discussion

The testing program had four objectives. The first objective is to determine the measurement accuracy of each transducer used by the measurement of the angle of enlargement of the ultrasonic beams (reflection angle). The second objective was to determine the variation of air and water permeability with W/C ratio and to compare this variation between the samples cured at air and the samples cured in water. The third and fourth objective was to establish and studying correlations between indirect UPV, attenuation and permeability, for the different concretes in the two modes of curing, and the influence of the size and frequency of transducers on these correlations.

3.1. *Influence of diameter and frequency of transducers on the angle of reflection*

The ultrasounds are generated by the transducers, the phenomenon that allows the transformation of a mechanical energy into electrical energy. All transducers have ultrasonic beam propagation. When the ultrasound beam reaches an interface, he can cross it or be thoughtful. The fraction of the beam which crosses the interface is the transmitted fraction, it continues its journey in depth. The non-transmitted and reflected fraction to the emission source. The angle of reflection is always equal to the angle of incidence of the beam [26-28].

We note in table 4 that the velocities determined by d' transducers are always higher than those determined by transducers D, D' and d. This is explained by the divergence of the ultrasonic beam; all transducers have beam spread. Figure 4 gives a simplified view of a sound beam for a flat transducer. In the near field, the beam has a complex shape that narrows. In the far field the beam diverges.

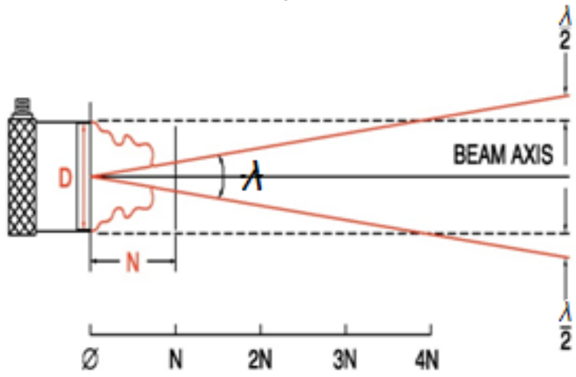

Figure 4: Enlargement of an ultrasonic beam

Equation (3) allows calculation of the half-angle spread in the far field:

$$Sin\left(\frac{\lambda}{2}\right) = 0.514\frac{V}{\phi.f} \tag{3}$$

Where V is the velocity and φ, f are respectively the diameter and the frequency of the transducers, it can be seen from this equation that beam spread from a transducer can be reduced by selecting a transducer with a higher frequency or a larger element diameter or both. For transducers of the same frequency and different diameter we find:

$$V_D = 1.40\ V_d \qquad \varphi_D = 6.6\ \varphi_d \qquad \sin(\lambda_D/2) = 0.2\ \sin(\lambda_d/2) \qquad \lambda_D = 0.2\ \lambda_d \tag{4}$$

and for transducers of the same diameter and different frequency we find:

$$V_D = 1.04\ V_{D'} \qquad f_D = 2.16\ f_{D'} \qquad \sin(\lambda_D/2) = 0.5\ \sin(\lambda_{D'}/2) \qquad \lambda_D = 0.5\ \lambda_{D'} \tag{5}$$

$$V_{d'} = 1.17\ V_D \qquad f_{d'} = 2.78\ f_D \qquad \varphi_{d'} = 0.58\ \varphi_D \qquad \sin(\lambda_{d'}/2) = 0.7\ \sin(\lambda_D/2) \qquad \lambda_{d'} = 0.7\ \lambda_D \tag{6}$$

from results (4), (5) and (6) we find that the d' transducers have the low divergence of the ultrasonic beam, where a better precision and a less disturbance of measurements by the transducers d' in this precise case.

3.2. *Air and water permeability*

Figure 5 illustrated the variation of the permeability depending on the W/C ratio. The results show that the air permeability and the water permeability increase with increasing W / C ratio. The relationship between these two parameters is linear. The correlation between the water permeability and the W/C ratio is less accurate for samples conserved in open air (R^2=0.67). Increasing the W/C ratio of 0.47 to 0.70 leads to an increase of almost 4 times of the air permeability for the two modes of conservation.

Table 4: Ultrasonic velocity and attenuation measured by different transducers

Transducers			Results of Velocity V (Km/s) and Attenuation α (dB/m)						
Symbol	ϕ (mm)	f (khz)	Concretes	OC 1	OC 2	OC 3	OC 4	OC 5	OC 6
d'	28.5	150	V	3.50	3.28	3.08	2.77	2.47	2.25
			α	- 20.87	- 24.44	- 21.52	- 24.78	- 23.51	- 30.33
D	49.5	54	V	2.94	2.67	2.53	2.37	2.18	2.06
			α	- 10.82	- 13.31	- 12.48	- 11.17	- 13.97	- 18.41
D'	49.5	25	V	2.76	2.63	2.46	2.26	2.10	2.03
			α	- 10.16	- 13.19	- 11.30	- 18.45	- 17.02	- 22.24
d	7.5	54	V	2.20	1.80	1.73	1.66	1.59	1.55
			α	- 12.55	- 15.24	- 15.49	- 27.41	- 30.18	- 33.96

The evolution of the water permeability with the W/C ratio is similar to the previous one for conservation in the water whilst to the conservation in the open air, the effect of W/C is low (11%). The mode of conservation affects much on the permeability to water as that to air. The ratio between the two modes varies from 3.6 to 5.7 for the air permeability and from 3.33 to 11.25 for the water permeability. For the samples conserved in water, the depth of water penetration of the different concretes always remains below the maximum allowable value for the impermeable concretes 50 mm (see Table 5). The results of the permeabilities obtained are consistent with those given by [29] in the case of the gas permeability and [30] in the case of water permeability.

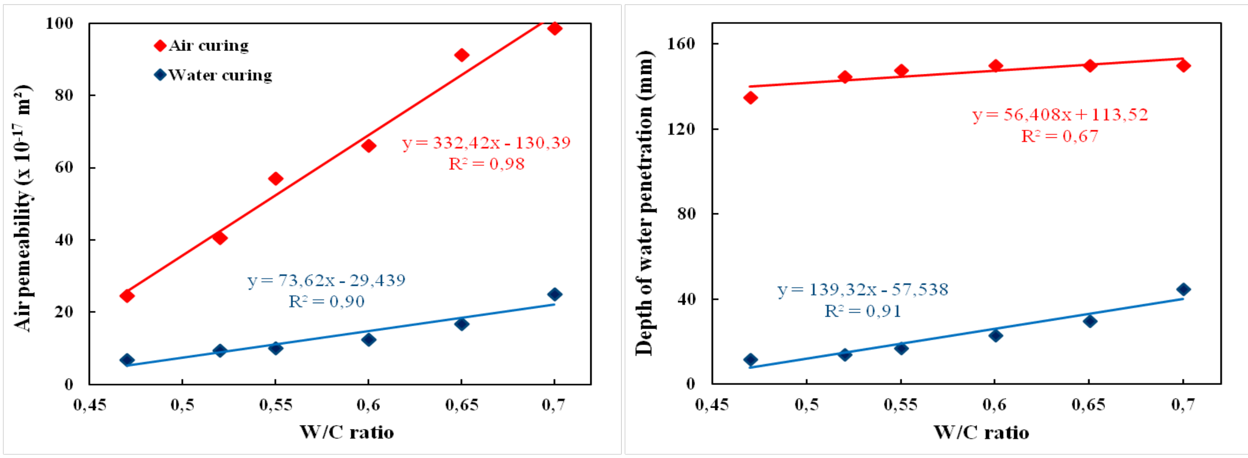

Figure 5: Variation of permeability with W/C ratio

Table 5: Air and water permeability of different concretes

Permeability		OC 1	OC 2	OC 3	OC 4	OC 5	OC 6
k_a x 10^{-17}	Air curing	24.5	40.5	57.0	66.1	91.2	98.5
	Water curing	6.8	9.4	10	12.4	16.7	25
h (mm)	Air curing	135	145	148	150	150	150
	Water curing	12	14	17	23	30	45

3.3. *Influence of permeability on velocity*

Fig 6 shows the variation of ultrasonic velocity in indirect mode as a function of air and water permeability. It is found that increasing the permeability lead to a decrease in velocity, this is valid for the two types of permeability in the two hygrometric states (water and air). A linear regression is performed on the relationships between the ultrasound speed and the permeabilities. The use of transducers d', D and D' lead to a fairly accurate presentation of these relationships by the linear regression. This is in concordance with the proportionality, observed by Ohdaira and Masuzawa [36] between the ultrasonic velocities and the water content of ordinary concretes. Lafhaj et al. [34] also observed a decrease in ultrasonic velocity with increasing permeability and porosity and an increase in this rate with water content. This relationship is much less precise with the use of the transducers d (see table 6), especially for conservation in the water because the water content of the material influences a lot permeability [31-33]. The water cure affects positively the correlation indirect UPV/permeability, especially for the water permeability. It is noticed that the highest value of the speed is related to the lower permeability, this is observed for the three different transducers. For concretes conserved in water (normalized tests) the correlation coefficients are very close (the difference does not exceed 4%) for the two types of permeability. it is also noticed for the low permeability concretes (W/C < 0.60), the increase of 82 and 92%, respectively of the air and water permeability in conservation mode in water, corresponds to a decrease of 11, 19, 18 and 25% of the velocities obtained respectively by the various transducers used (d', D, D', d), by against for the important permeability concretes (W/C ≥ 0.60), an increase of 50% of the air and water permeability is reflected by a decrease of 8, 5.5, 3 and 2.5% for the velocities obtained respectively by the transducers (d', D, D', d). These results are consistent with those obtained by Panzera et al. [35] where they found that a 3% decrease in the ultrasonic wave velocity (obtained by transducers with a frequency of 50 kHz) for ordinary concretes corresponds to an increase in oxygen permeability of 46%. It is noted that the effect of the frequency of the transducers is minimal for the evolution of correlations (transducers d', D and D') for the different concretes. The size of the transducers (D and d) is more sensitive, for the plastics concretes than for the fluid concretes, in these correlations. The increase of size of transducers improves the correlation (velocity-permeability) especially for concretes conserved in the open air, this can be explained by the divergence of the reflection angle ($\lambda_D = 0.2\ \lambda_d$) and confirmed by the result ($\lambda_D = 0.25\ \lambda_d$) obtained by Benouis and Grini [28] in the study of the correlations between the velocity of ultrasonic waves and the porosity of concrete. The best correlations are given by the transducers d' which have the slightest divergence of the reflection angle.

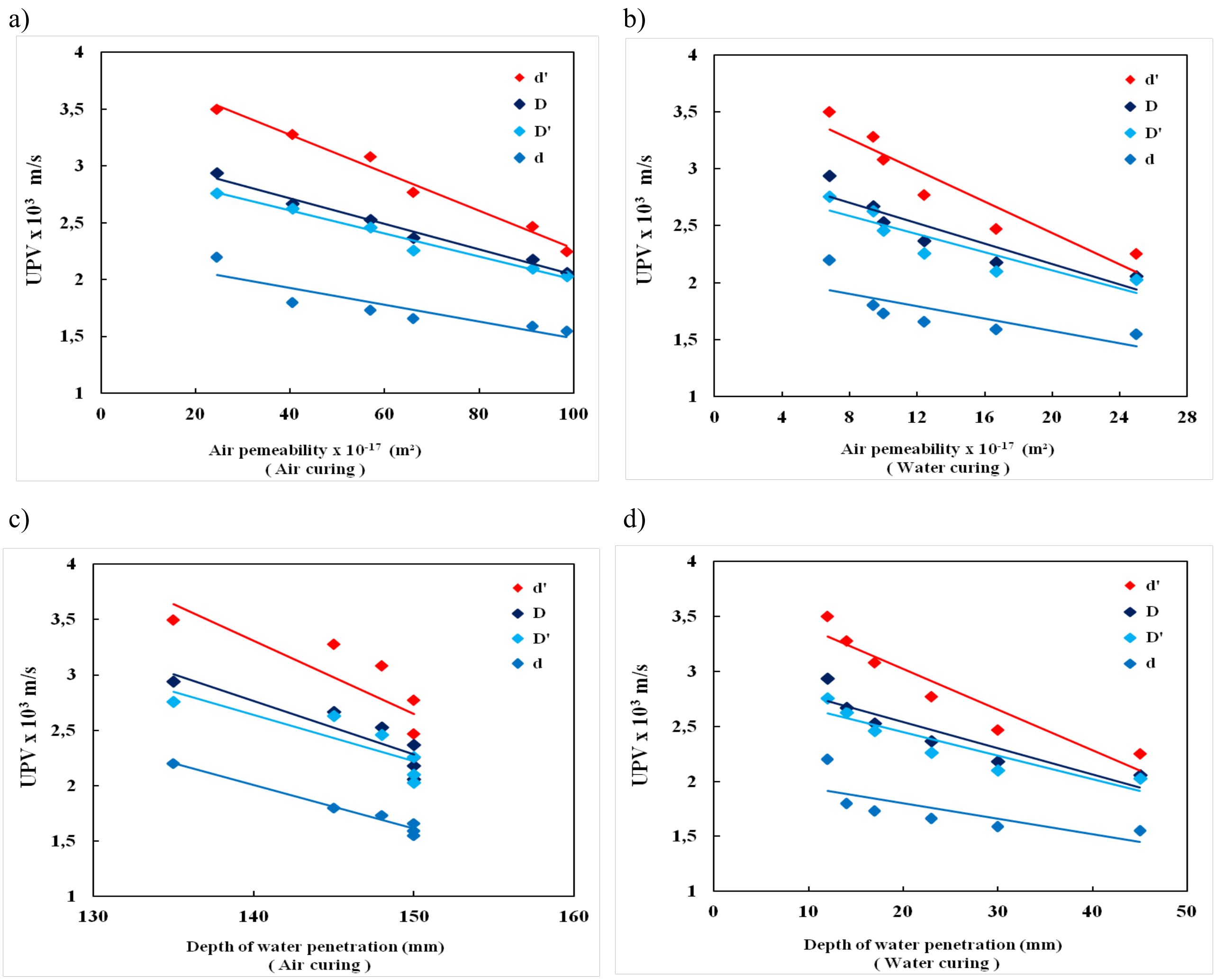

Figure 6: Evolution of IW velocity with permeability.

Table 6: Results of linear regression of data from Fig. 7: regression coefficient (R^2).

Regression Coefficient (R^2) of correlation IW Velocity/permeability					
Figure		a	b	c	d
Transducers	D	0.98	0.84	0.78	0.84
	D'	0.98	0.80	0.70	0.83
	d	0.80	0.57	0.97	0.54
	d'	0.98	0.88	0.65	0.90

3.4. *Influence of permeability on attenuation*

Fig 7 shows the variation of attenuation of indirect waves as a function of air and water permeability. We observe for the two hygrometric states, the attenuation obtained by the four transducers increase with the increasing of the two types of permeability, Contrary to the velocity (see paragraph 3.3). An almost linear regression is observed between the attenuation and the permeabilities. The water curing increases the slope of the dependence between the attenuation and the two types of permeabilities; this corresponds to its effect on the relations between velocity and permeability (section 3.3). This result is consistent with that obtained by Abraham et al. [38] they observed that when the quality of the concrete increases (i.e, decrease in porosity and permeability) the attenuation values and velocities obtained by non-contact transducers evolve in a similar way with a decrease in attenuation and an increase in speeds. For the permeable concretes (W/C ≥ 0.60), the attenuation shows a large increase, this can be justified by the significant changes in the microstructure of the concrete when the W/C ratio increases.

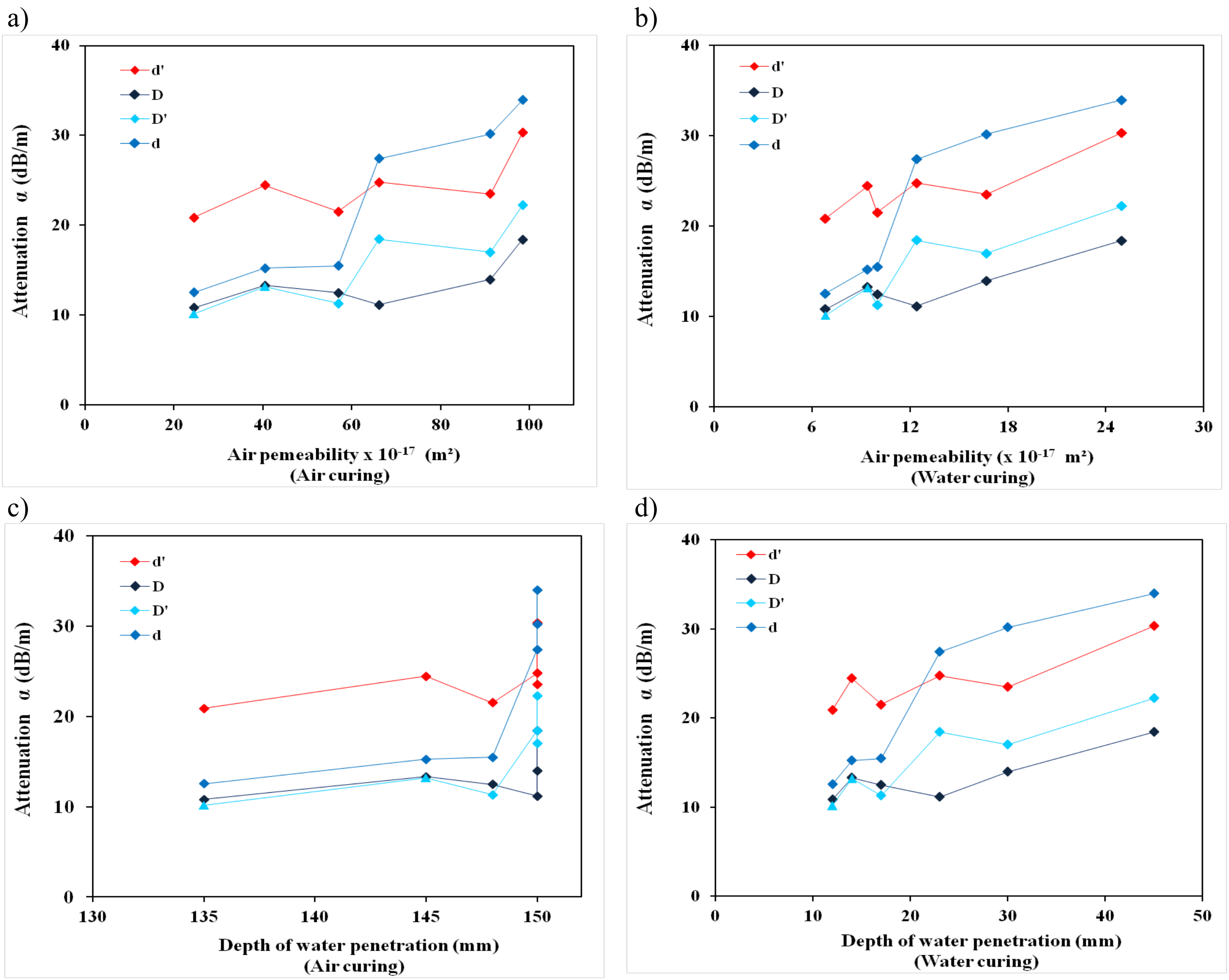

Figure 7: Evolution of IW attenuation with permeability.

Lafhaj et al. [34] reported that the attenuation is not only sensitive to porosity and permeability, but also to a change of microstructure in the mortar when the w / c ratio is higher than 0.45. This steep increase in attenuation may be related to the diffusion of the ultrasonic wave by pores of increasing size. For the specimens-preserved in open air, the increase in the diameter of the transducers decreased the correlation between attenuation and permeability of 37% for air permeability and 55% for water permeability. Test specimens conserved in water the difference does not exceed 1% for air permeability and 11% for water permeability, this can be justified by the effect of water content on the diffusion phenomenon [37-38]. It is also noted that each time the frequency of the transducers increases, the correlation coefficient (R^2) decreases in both types of permeability for the two conservation modes (see table 7), this means that the increase in the frequency of the transducers give waves more attenuated which requires a more thorough analysis for the signals, this latter shows a high sensitivity in the quantitative estimation of the permeability by attenuation, thus it is concluded that the attenuation is more complex to measure in situ especially for a heterogeneous material such as concrete.

Table 7**:** Results of linear regression of data from Figure 7: regression coefficient (R^2).

Regression Coefficient (R^2) of correlation IW attenuation/permeability					
Figure		a	b	c	d
Transducers	D	0.56	0.89	0.50	0.75
	D'	0.83	0.82	0.78	0.82
	d	0.25	0.55	0.31	0.51
	d'	0.76	0.86	0.75	0.84

Conclusions

The overall objective of this research is to find a reliable correlation between indirect UPV, attenuation, air permeability and water permeability of concretes, thus the impact of the size and the frequency of contact transducers on this correlation. The results of the series of experimental measurements lead us to the following main conclusions:

- Changes in velocity are more visible in low permeability concretes, but attenuation is more affected by permeable concretes.
- Decreasing in the reflection angle of the transducers improves the correlation between indirect UPV, attenuation and permeability.
- The increase in the diameter of the transducers improves the correlations between UPV and permeability, and has led to a decrease in correlations between attenuation and permeability.
- The increase in the frequency of the transducers negatively affects the quality of the attenuation/permeability correlation and does not have an important influence on the improvement of the velocity/permeability correlation; this requires a more in-depth analysis for the obtained signals and the microstructure of concrete.

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