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Determination of volumetric water content of concrete using ground-penetrating radar

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Abstract

A large number of reinforced or prestressed concrete pathologies require the presence of water to develop. In this context, the quantification of water content is an important phase for the diagnosis of concrete. The propagation of electromagnetic waves is controlled by its electromagnetic properties, mainly influenced by the presence of water in the case of concrete. We propose to use the direct transmitter–receiver radar wave to determine the moisture of the cover concrete. The Wide Angle Reflection Refraction (WARR) measurement technique is used to obtain the speed of the direct wave. A method is used to extract the group and the phase velocity of this wave. We show that the speed is not dependent to the frequency between 300 MHz and 1.2 GHz in these testing conditions. By using two different concretes partially saturated, we show that there is a linear relation, independent of the concrete, between the volume water content and the propagation velocity of the direct wave on the one hand and its attenuation on the other hand.

Keywords: (A) Humidity, microwave processing; (C) Durability, electromagnetic properties; (E) Concrete

1. Introduction

Many structures reach a critical phase of aging at which time damage, like reinforcement corrosion, can affect their serviceability. The degradations observed are often due to external causes. The cover concrete protects the structural elements and, more particularly, the reinforcement. Its level of degradation is a good indicator of the structural quality and its evaluation should enable the structure to be replaced within its life cycle. For this reason, some reliable, non-destructive tools are required for structure diagnosis.

Chemical attack can stem from an ingress of aggressive agents (e.g. corrosion can follow carbonation or chloride ingress) or from an internal reaction (alkali-silica or sulfatic reaction). For all these pathologies, the common catalyst is moisture, since all the chemical reactions (corrosion, alkali-silica, sulfatic, etc.) need some water to develop. The quantification of moisture surface gradients is an important phase in the diagnosis. Methods based on the propagation of electromagnetic waves, mainly used for the characterization or detection of geometry, could have new applications in this context. Former studies have used this technique by mean of TDR systems [1] or by exploitation on the absorption of continuous microwaves between two dipole antennas, which are positioned inside two parallel boreholes [2]. These results provide the value of dielectric constant or of the electromagnetic attenuation which can be linked to the volumetric water content. But these techniques need to drill a hole in the concrete to carry out the measurement. So its not totally a non-destructive testing method and the number of measurements is necessarily limited. An attractive alternative consists on using ground-penetrating radar and more particularly the direct wave which directly propagates from transmitter to receiver. Some studies have shown that the energy directly radiated by the transmitter towards the receiver, named the direct wave or ground wave, can provide reliable data on the coupling material properties [3,4]. The influence of water content on the direct signal attenuation has been highlighted [5–7]. This signal is of great interest for two reasons: first, it does not require the presence of reflectors and, second, as it propagates through the subsurface, it can provide information on the cover concrete, which is very important for reinforced concrete durability. Up to now only the

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amplitude of the direct wave is analyzed, this paper is also focused on the speed variation of this wave versus volumetric water content. This speed is calculated by mean of an original technique which has been previously reported by the authors [8].

In this study, twelve concrete samples, made of two concrete compositions with different porosities and aggregates sizes, were prepared at different homogeneous saturation degrees in order to study the effects of the water content on the radar waves.

2. Radar principle, application to civil engineering

The general principle of radar sounding of civil engineering structures, based on the propagation of electromagnetic impulses, has been reported by many authors [9,10]. Used in the ground-coupled bi-static configuration (the transmitter and the receiver are dissociated) the radar technique is conceptually quite simple. The essential features are a source antenna (transmitter (T)) placed on the material surface, radiating energy both upward into the air and downward into the material, and an antenna receiving the signal transmitted by the source (receiver (R)). One wave is the material wave, propagating along the air–material interface in the subsurface with a speed determined by the upper part of the subsurface [11–13]. This wave is not a surface wave like a Rayleigh wave but a direct wave from transmitter to receiver, i.e. a part of the radiating energy directly propagates along the air–material interface in the subsurface [14]. Calculations and simulations have shown that the theoretical penetration depth of the material wave is around one wave length for a radar pulse duration of 1 ns. In practice due to an insufficient signal-to-noise ratio of the system, this value is probably less important. Generally, little attention is paid to this wave but it is possible to extract electromagnetic (EM) information from it without any reflector in the material. The possibilities offered by the use of this wave for the evaluation of moisture or chloride contents have been demonstrated by previous studies [15,16].

During its propagation in concrete, an electromagnetic (EM) wave is modified in relation with the EM properties of the material: the electrical conductivity, σ, the dielectric permittivity, ε, and the magnetic permeability, μ. The latter is equal to the free space permeability μ_0 since concrete is a non-magnetic material ($\mu_0=4\pi\cdot10^{-7}$ H/m).

These properties have been defined from a theoretical point of view, in order to separate the basic electrical phenomena. However, in the usual range of radar frequencies (~100 to 3000 MHz), EM waves are influenced by both electrical conductivity and dielectric permittivity, and it is impossible to distinguish their effects. Thus, an effective permittivity, ε_e, is defined, which takes σ and ε into account.

The permittivity ε_e is generally divided by the permittivity of air ε_0, which is a real number ($\varepsilon_0=8.854.10^{-12}$ F/m). A relative permittivity ε_r is thus defined. The real part ε_r' of the relative permittivity is usually known as the dielectric constant and represents the amount of electromagnetic energy stored as electrical polarization. The imaginary part, ε_r'' (loss factor), represents the losses of energy due to absorption. It greatly influences the attenuation of the wave.

In media with low losses, like concrete, this equation can be approximated by Eq. (1):

$$v(\omega)=\frac{c}{\sqrt{\varepsilon_r'(\omega)}} \tag{1}$$

Eq. (1) shows that the wave speed in concrete depends only on ε_r' (c is the velocity of light in free space).

3. Speed analysis

In radar sounding, speed measurements are generally carried out when the distance between transmitter and receiver (offset) can be varied (Fig. 1), Wide Angle Reflection Refraction (WARR) [17,18] acquisition consists of increasing the distance between the antennas while one of them remains stationary.

We used two techniques of processing the signal to determine the propagation velocity of the direct wave in material. Each of these techniques presents advantages and disadvantages.

The direct measurement of the travel time of the direct wave by the WARR technique makes it possible to obtain the propagation velocity of the maximum of energy of this wave easily. For that, the arrival time of the material wave is plotted for each offset and the inverse of the slope of the straight line gives the speed of this wave. The velocity thus determined can be comparable to the group velocity of the direct wave. However, the attenuation and the dispersion rate according to the frequency of this electromagnetic wave can significantly modify the form of the wave transmitted between the various positions of receiver. This can affect the velocity measurement based on the determination of the travel time of the maximum of amplitude between the various positions of receiver.

The velocity measurement based on the spectral analysis of the radar surface wave (SARSW) between the signals received for each pair of receiver positions provides information on the phase velocity of the direct wave according to the frequency [8].

For a given position of the transmitter, two signals are recorded for two different positions of the receiver. The two windowed time domain records are transformed in the frequency

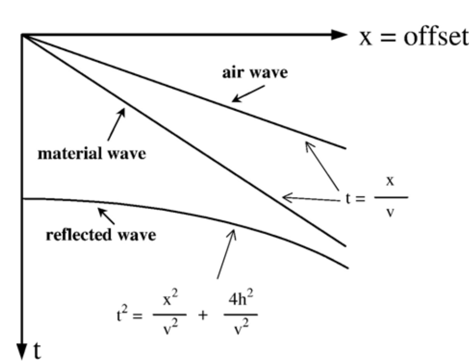

Fig. 1. Schematic WARR measurement for a homogeneous material. It represents the travel time of different signals versus the offset. The material wave can be identified as a wave moving linearly out from the origin of the x–t plot (h is the thickness of the slab).

domain through a Fourier transform. The phase of the cross power spectrum represents the number of cycles of a given frequency between the two receiver locations. Then a phase unwrapping processing is implemented in order to find the actual phase of each frequency. This processing consists in counting the number of full 2π radian cycles preceding the frequency and in adding this value to the fraction of the last cycle of the frequency. By using the principle of a rotating vector, a phase shift of 2π radians is equivalent to the travel time of one period. Once the phase spectrum is unwrapped, travel time between the two receiver positions can be calculated for each frequency. Since the distance between the receiver positions is known, the material wave speed can be calculated as a function of frequency.

Moreover, the use of a Fourier transform makes it possible to free calculations from the modification of the form of this wave during propagation. However, this technique is much more complex to implement and takes into account only one pair of receiver positions per measurement, which increases the measurement noise in comparison with a technique which takes all the received signals into account.

4. Experimental details

4.1. Sample details

Twelve samples were designed and prepared in order to avoid any bias in the measurements from border effects or uncontrolled reflection. The calculation of the dimensions of these slabs based on the duration of the radar pulse led us to make $60 \times 60 \times 12$ cm slabs. The slabs were covered with aluminum foil on all the faces except the measurement face. This allowed the slab to be sealed and also ensured perfect reflection of the radar waves on these faces. In order to study the effects of the water content (tap water) on the radar waves we used concrete slabs having different water contents.

4.2. Concrete composition and characteristics

Two compositions were chosen, C1 and C2 (Table 1), for the concrete slabs in order to obtain concretes with different porosities and different aggregate sizes. The concretes had water-to-cement ratios of 0.66 and 0.48 respectively. The water accessible average porosity measured after total absorption was 15.3% for C1 and 12% for C2.

Table 1
Concrete mixes

	C1	C2
Component	Content (kg/m^3)	Content (kg/m^3)
Cement CEM I 52.5	300	385
Sand (rounded, siliceous 0/4)	828	660
Gravel (rounded, siliceous 4/10)	1078	415
Gravel (rounded, siliceous 10/20)		750
Water (l/m^3)	210	185
W/C (water on cement ratio)	0.66	0.48
G/S (gravel on sand ratio)	1.30	1.77

Table 2
28-day compressive strength for C1 concrete

	Compressive strength 28 days (MPa)	Standard deviation (MPa)	Discrepancy (%)
C1 — Batch 1	34.6	0.50	1.42
C1 — Batch 2	38.5	0.90	2.04
C1 — Batch 3	38.7	1.10	2.74
Average	37.3	0.83	2.07

Tables 2 and 3 give the values of compressive strength measured on 3 cylinders (h=22 cm and d=11 cm) for each samples (CX-Y) after 28 days of storage in water. The pairs of samples, presented in Tables 2 and 3, are made from the same batch.

4.3. Control of water content

The aim was to provide slabs at different degrees of saturation, with a uniform distribution of water in the slabs. Six slabs were obtained for each concrete composition. The concrete age was at least 90 days.

The procedure was as follows:

- Saturation until weight was constant,
- Weighing,
- Oven-drying at 80 °C until weight was constant,
- Water absorption by capillary absorption from dry state up to target degree of saturation by controlling the weight of the samples,
- sealing of all the faces with aluminum foil,
- oven-drying at 80 °C for 2 months to make water volume uniform.

The weight of the samples is checked at the end of the conditioning procedure in order to ensure that there was no weight loss.

Radar measurements were taken on these various slabs when they were dry and saturated, which provided measurements for two additional degrees of saturation, 0 and 100%.

4.4. Radar equipment and measurement process

Generally, for commercially available coupled antennas, the transmitter and receiver are in one box, so the distance between them is always the same. Two antennas are therefore required to make measurements with various distances in the Wide Angle Reflection Refraction (WARR) technique.

Table 3
28-day compressive strength for C2 concrete

	Compressive strength 28 days (MPa)	Standard deviation (MPa)	Discrepancy (%)
C2 — Batch 1	35.1	0.50	1.62
C2 — Batch 2	34.9	0.48	1.37
C2 — Batch 3	35.2	0.76	2.15
Average	35.1	0.58	1.71

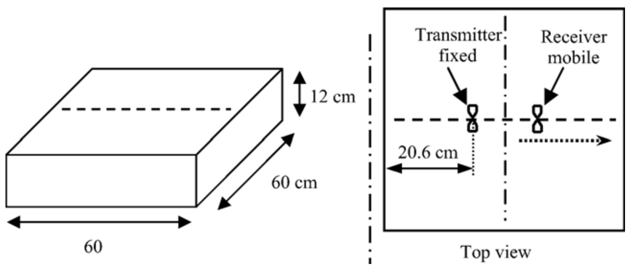

Fig. 2. Slab dimensions and positions of transmitter and receiver during measurement using WARR technique.

Radar measurements were carried out using a SIR-2000 radar system, equipped with two 1.5 GHz coupled antennas (5100) both developed by GSSI. The GSSI-5100 antenna is a double coupled antenna made up of two dipolar elements, one used as the transmitter and the other as the receiver. When two antennas were used simultaneously to change the receiver–transmitter distance, only the transmitting part of one antenna and the receiving part of the other were active. In this case, the other parts of the antennas had no active role in the emission or the reception of the radar signals.

4.4.1. Measurement of direct wave velocity

In order to measure the propagation velocity on the slab under study, we used the two radar antennas according to the Wide Angle Reflection and Refraction (WARR) technique (see Fig. 2). In this configuration, the transmitter remained fixed throughout the test whereas the receiver moved to eleven different positions spaced out 1 cm with a minimal offset 15.9 cm.

In order to accurately measure this distance the antenna device has been opened in a previous study [14]. For each receiver position, we recovered a radar signal representing the amplitude of the electric field. For a given position, each radar signal reported is the average of 10 received signals. Apart from the application of a constant amplification applied to the signal to facilitate the measurement, the data were recorded without processing or by pass filtering. This type of measurement enabled us to obtain the propagation velocity of the direct wave by the WARR technique and the phase velocity by the SARSW technique.

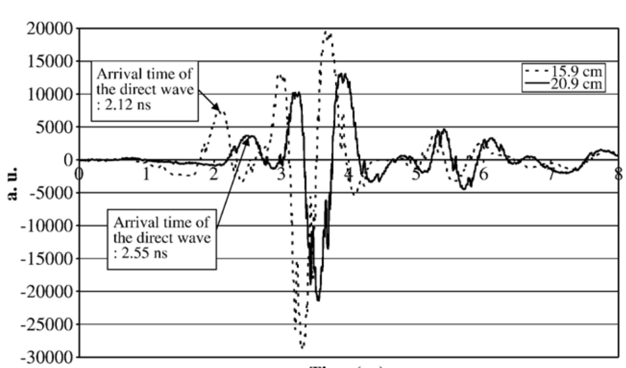

Fig. 3. Two recorded radar signals for a respective offset of 15.9 cm and 20.9 cm.

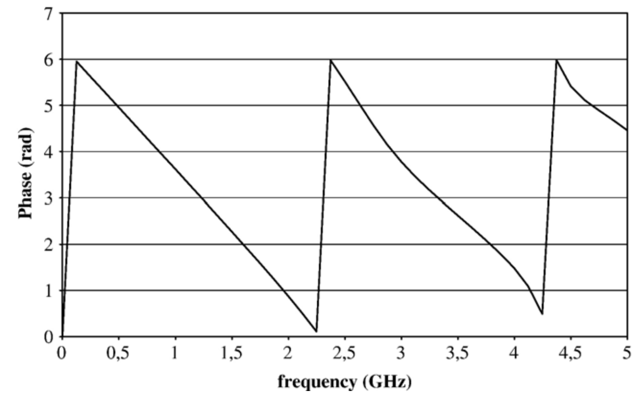

Fig. 4. Wrapped phase spectrum of the cross power spectrum of the two radar signals presented in Fig. 3.

Fig. 3 shows two recorded signal and the arrival time of the material wave for an offset of 15.9 and 20.9 cm. This allows us to evaluate the group speed of the material wave at 11.63 cm/ns for a volumetric water content of 6.26% of a C1 concrete slab. Fig. 4 shows the wrapped phase spectrum of the cross power spectrum of these two radar signals. When the phase spectrum is unwrapped we obtain a phase velocity of 11.77 cm/ns at 1 GHz with no dispersion in the 300 MHz–1.3 GHz range.

By using the SARSW technique [8] we obtained 55 values of phase velocity corresponding to the different possibilities of coupling the receiver positions. In order to simplify the analysis we took the average of these various results. Moreover, we did not observe significant dispersion of these results versus frequency, so we only show the phase velocity obtained for the frequency of 1 GHz, which approximately corresponds to the center frequency of the direct wave when the antennas are coupled with concrete material [16].

4.4.2. Measurement of wave amplitudes

In addition to these bi-static measurements, we took measurements with only one GSSI 5100 antenna placed at the center of the slab. The radar data were recorded without any processing. Each signal reported corresponds in fact to an average of 500 radar signals. The goal of these measurements was to analyze the variation of the amplitude of the direct wave, and also of the reflection on the bottom of the slab. Several amplitude values were recorded: the maximum of the positive

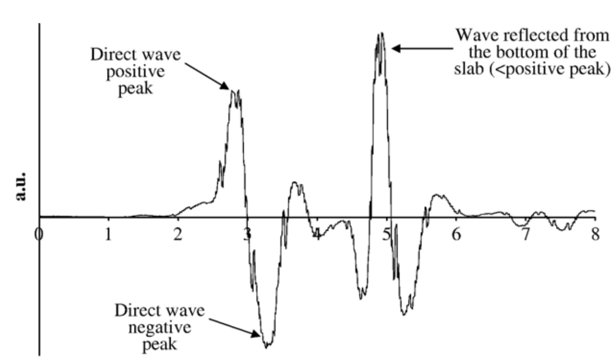

Fig. 5. Example of radar signal obtained using one antenna on concrete slab.

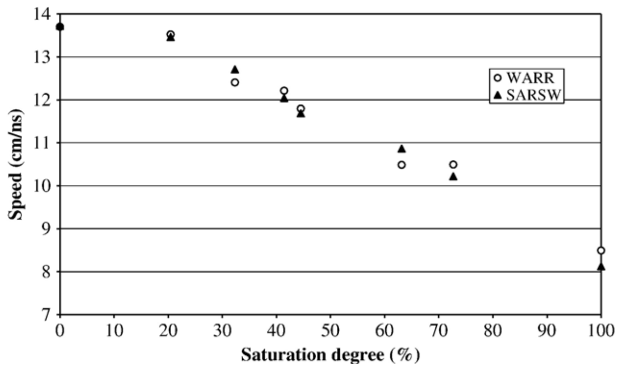

Fig. 6. Speed variation versus saturation degree for C1 concrete.

and negative peaks of the direct wave, the maximum of the positive peak of the reflection of the wave from the bottom of the slab, and the maximum of the positive peak of the direct wave when the antenna was emitting in air. Fig. 5 presents a characteristic amplitude versus time diagram (radargram) obtained with only one antenna on the slab. On this radargram, the first positive and negative peaks represent the direct transmitter–receiver wave. The positive peak of the reflection, with a negative peak on either side, represents the reflection from the bottom of the slab.

5. Effect of water content on speed and amplitude of radar waves

5.1. C1 concrete

Fig. 6 presents the speed variation of the direct wave according to the saturation degree of the C1 slab. These results bring together the speed measurements obtained directly by analysis of the travel time of the direct wave by the WARR technique, and the phase velocity obtained for the frequency of 1 GHz by the SARSW technique.

The speed measurements presented for 0 and 100% saturation correspond to averages of the speed measurements obtained on all the slabs in the dry and saturated state. The coefficient of variation obtained for dry slabs was 7.1% for direct measurement of travel time and 6.6% for SARSW treatment. On fully saturated slabs, this coefficient of variation decreased to 2.8% for direct measurement of travel time and 2.1% for SARSW treatment.

These curves show the good linear correlation between the degree of water saturation of the concrete slab and the speed of the direct wave. Moreover, the speed measurements obtained with the two techniques give approximately the same results. Thus the speed varies from 14.3 cm/ns for a dry concrete to 7.8 cm/ns for a saturated concrete, which corresponds to a dielectric constant variation from 4.4 to 14.8.

The curve shows a plateau between 0 and 20% saturation. Several hypotheses can explain this phenomenon:

- In this range of saturation degree, the majority of water present in the slab is no longer free water but bound water (adsorbed on the surface of the pores). The polarization aptitude of bound water is more limited than that of free water and consequently the dielectric constant of the concrete, and thus the speed of the direct wave does not vary in this range of degrees of saturation.
- The shape of the direct wave can be altered by the reflection on the bottom of the concrete slab. Actually, the lower the dielectric constant, the higher the speed and the more probable an interaction between the direct wave and the reflection from the bottom of the slab. This is particularly highlighted for the highest offset.
- The direct signal in the air can disturb the speed measurement as a high speed of the wave in the material makes it more difficult to dissociate the direct wave in the air from the direct wave in the material [14]. This is particularly true for the smallest offset.

Fig. 7 presents the variations of the peak-to-peak amplitude of the direct wave and of the positive peak amplitude of the wave reflected on the bottom of the slab obtained with only one antenna. The amplitudes have been normalized, i.e. divided by the amplitude of the maximum of the positive peak of the direct wave when the antenna was emitting in air. The amplitude values presented for dry concrete correspond to averages of amplitudes obtained on the whole of the slab in a dry state. The coefficients of variation obtained on dry slab are 0.8% for the peak-to-peak amplitude of the direct wave and 0.6% for the positive peak amplitude of the reflected wave.

The direct wave and reflected wave amplitudes decrease as the saturation degree of the concrete increases. It can be observed that the amplitude of the direct wave varies more slowly than the amplitude of the reflection from the bottom of the slab. This can be simply explained by the fact that the distance traveled by the reflected wave through the material is longer than the path of the direct wave.

We can see that the curves do not present a plateau for saturation degrees lower than 20%. Here, the distance from the transmitter to the receiver is 5.9 cm, which is shorter than the transmitter–receiver distance during speed measurement (15.9 cm minimum). Moreover, there is no direct wave in the air between transmitter and receiver because of the electromagnetic shield of the antenna. In this configuration there is no possible interaction between the direct wave in the material and

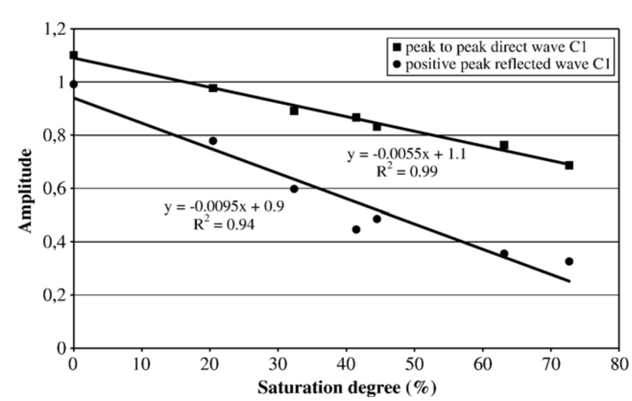

Fig. 7. Normalized amplitude versus saturation degree for C1 concrete.

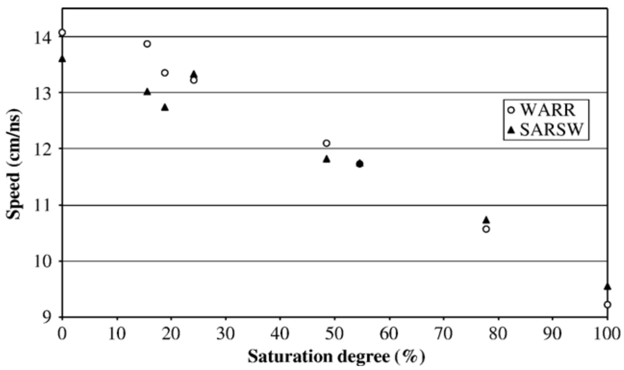

Fig. 8. Speed variation versus saturation degree for C2 concrete.

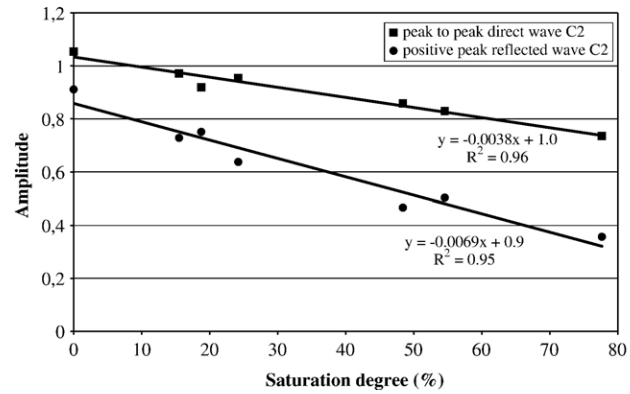

Fig. 9. Normalized amplitude versus saturation degree for C2 concrete.

the direct wave in the air or the reflected wave. Therefore, the plateau on the speed curves probably comes from an interaction between the direct wave in the material and the direct wave in the air or the reflected wave and does not come from a variation of the dielectric properties of the concrete due to bound water. Because, even if the variation of absorption is not intended by the same physical effect than the variation of velocity, the presence of bound water in this range of saturation degree must intend the variation of amplitude. Actually, if the water dipoles are less mobile the absorption by polarization should be, at the same time, less important.

5.2. C2 concrete

The speed variations of the direct wave and the amplitude variations of the direct wave and of the reflected wave for the C2 concrete slabs are presented. As for C1 concrete slabs, the speed measurements presented for the saturation degrees of 0 and 100% correspond to the average of speed measurements taken on all the slabs in the dry and saturated states. The coefficient of variation obtained on dry slab is 6.5% for the direct measurement of travel time and 5.7% for SARSW treatment. On fully saturated slab this coefficient of variation decreases to 2.1% for direct measurement of travel time and 2% for SARSW treatment.

Fig. 8 shows the direct wave speed variation according to the saturation degree of the C2 slabs. As for C1 slabs, these results bring together the speed measurements obtained by analysis of the travel time of the direct wave by the WARR technique and the phase velocity obtained at the frequency of 1 GHz by SARSW. Speed thus varies from 14.1 cm/ns for a 0% of saturation to 9.2 cm/ns for total saturation, which corresponds to a variation of dielectric constant from 4.5 to 10.6.

For saturation degrees ranging between 24% and 100% there is a linear relationship between the speed and the saturation degree, as there was for the C1 slab. Moreover, for this range of saturation degrees, the speed values obtained with the two processing methods are very close. As for C1, we can observe that the curve presents a plateau between 0 and 20% saturation.

Fig. 9 presents the variations of the peak-to-peak amplitude of the direct wave and of the positive peak amplitude of the reflected wave obtained with only one antenna on C2 slabs. As for C1 slabs, the amplitudes have been normalized and, for the dry concrete, the plotted value is the average of the amplitudes obtained for the six slabs in a dry state. The coefficient of dispersion obtained on dry slab is 1.3% for the peak-to-peak amplitude of the direct wave and 8.1% for the positive peak amplitude of the reflected wave.

Due to the procedure used for sample preparation, we do not have any measurement of amplitude on saturated slabs because, in this case, there was no aluminum foil on the slab to ensure perfect reflection of the waves.

We find the same type of result as on C1, i.e. the amplitude of the direct wave and of the wave reflected on the bottom of the slab is inversely proportional to the water saturation degree of the concrete and the reflected wave amplitude varies more than the direct wave amplitude. As for C1, the curves do not present a plateau for saturation degrees lower than 20%, which may confirm again that the plateau on the speed curves comes from an interaction between the direct wave in the material and the direct wave in the air or the reflected wave.

5.3. Comparison of C1 and C2 measurements

Fig. 10 presents the speed measurements obtained by the two techniques used for the C1 and C2 concrete slabs. On these curves, we have voluntarily removed experimental measurements for saturation degrees lower than 20% since we have seen that, for these saturation degrees, the speed measurements were disturbed by interferences. In order to facilitate the reading of

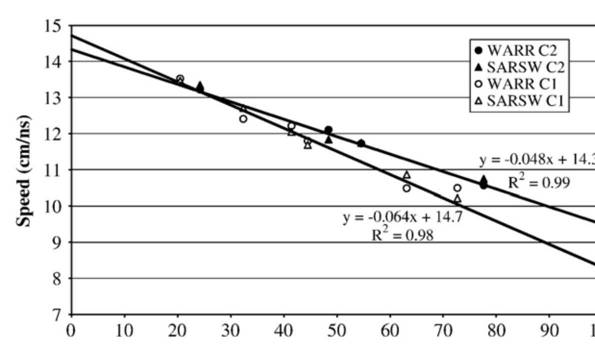

Fig. 10. Speed variation versus saturation degree for C1 and C2.

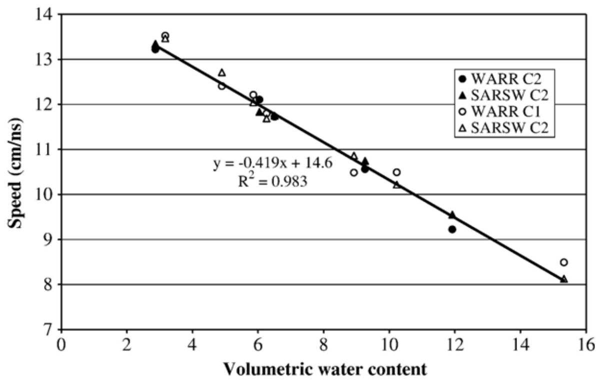

Fig. 11. Speed variation versus volumetric water content for C1 and C2.

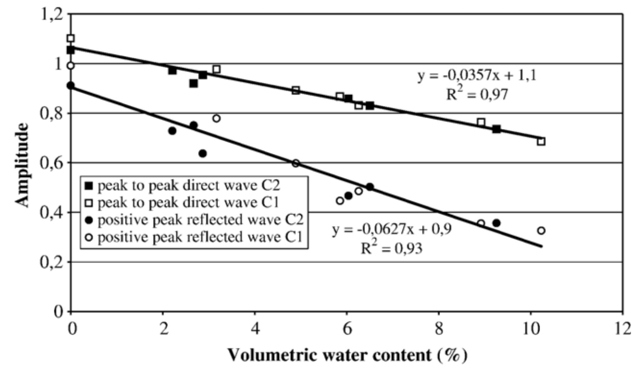

Fig. 13. Normalized amplitude versus volumetric water content, C1 and C2.

these results, we performed a linear regression on each series of measurements.

It can be noted that the slope of the straight line linking the speed to the saturation degree is greater for C1 than C2. Using Eq. (1) and making the assumption that the two straight regression lines of speed reflect reality, the value of the dielectric constant varies from 4.1 on dry slabs to 13.1 on saturated slabs for C1 concrete and from 4.4 on dry slabs to 9.9 on saturated slabs for C2 concrete.

The amplitude of variation of the dielectric constant is greater for the C1 concrete than for the C2. These results can be explained because the open porosity is higher in C1 than in C2 and, consequently, for the same degree of saturation, the interstitial water content is higher for C1 than for C2. The accessible porosity measured after total absorption is 15.3% for the C1 concrete and 12% for the C2 concrete.

Fig. 11 shows the speed variations according to the volume of water relative to the volume of the concrete slab (volumetric water content). It shows that the speed variation of the direct wave in concrete depends linearly on the volumetric water content alone, whatever the type of concrete used in this study or its intrinsic porosity. In this case, only water decreases the direct wave speed. This result is interesting with respect to the practical applications of the technique since the speed measurement alone would make it possible to evaluate the volumetric water content of a concrete independently of the other relevant parameters.

Fig. 12 presents the amplitude variations of the direct wave and of the wave reflected from the bottom of the slab, according to the saturation degree of the two concretes C1 and C2. We

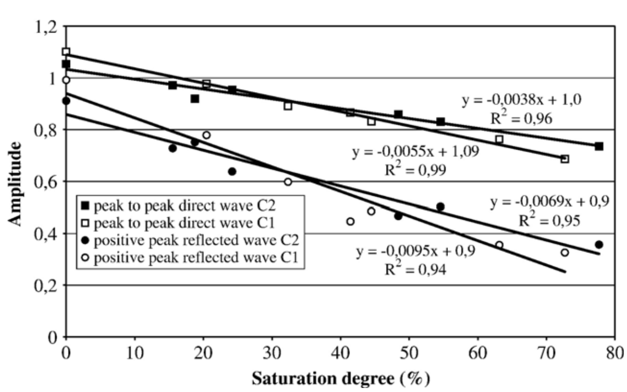

Fig. 12. Normalized amplitude versus saturation degree, C1 and C2.

obtain the same kind of result as for the direct wave speed. The amplitude variations are slightly greater for C1 than for C2.

Fig. 13 presents the amplitude variations of the direct wave and the reflected wave according to the volumetric water content for C1 and C2. The variation of amplitude according to the volumetric water content is, as for the speed variation, linear.

6. Conclusion

Radar technique is chosen because regarding other available techniques [1,2], this is a fast and a totally non-destructive testing method.

The use of the SARSW technique makes it possible to find the phase velocity of the direct wave and its dependence on the frequency. For a material with weak losses, such as concrete, it is thus possible to measure the dielectric constant and so to establish the relation between dielectric constant and frequency. But, in this study, we did not note a dispersive character of the concrete. Some additional tests are now being performed to check this observation. For this purpose, we have developed an experimental setup to measure electromagnetic properties in the 300 MHz–1 GHz frequency range by means of a coaxial line.

The direct wave is very relevant for on-site applications because it does not require a reflector and, moreover, it enables the subsurface of the concrete structures to be investigated. A numerical simulation [14] showed that the penetration depth of the direct wave was not greater than the wavelength. Some additional simulations are required to define the effect of property gradients more accurately, in particular regarding water content.

The experimental results obtained on concrete slabs with controlled water content as a whole show that the direct wave speed and its variation of amplitude are linearly linked to the volumetric water content of the concrete, independently of its porosity. Both attenuation and velocity are sensitive to moisture and they vary in the same way. The exploitation of the radar direct wave on real structures would make it possible to determine the volumetric water content of the concrete by the exploitation of two parameters, attenuation and speed of the material wave. Compared to other techniques using only one parameter, this is an interesting result because the variation of absorption is not intended by the same physical effect than the variation of the velocity (e.g. absorption also strongly depends on the salt content), so the use of the variation of speed and amplitude could give an estimation of both volumetric water content and salt content (especially chloride content). At the present time, some studies are being implemented on laboratory samples for which the water and chloride content are controlled in order to check this hypothesis. In these studies we will also try to quantify the variability of the measurement for large variations of concrete porosity, type of aggregates, etc. About 10 samples for 9 different concretes will be made and tested at different saturation degrees. So the variance of the measurement linked to the variability of the samples will be quantified. The variability of the fabrication will be also quantified by testing two identical concretes batched at two different times.

Up to now, this measurement technique can be implemented on concrete structures with some recommendations. Some measurements done on irregular shaped structures showed that there is no problem if the surface irregularity does not exceed 1 cm. Concerning structures containing reinforcement it can be difficult to separate the material wave from the reflected wave on the rebars. With this kind of antennas, the lowest offset value for which the speed measurement can be implemented is 15.9 cm. Then the minimal distance between two bars must be at least 25 cm to make possible the speed measurement between the bars.

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References

[1] V. Janoo, C. Korhonen, M. Hovan, Measurement of water content in Portland cement concrete, Journal of Transportation in Civil Engineering 125 (3) (1999) 245–249.

[2] F. Weise, D. Schaurich, "A novel combination of NDT-methods for assessment of moisture conditions in structural members—a case study of th Berlin Zeughaus" Non-destructuve Testing in Civil Engineering, 2003, proceeding in cdrom.

[3] S. Laurens, J.-P. Balayssac, J. Rhazi, G. Arliguie, Influence of concrete moisture upon radar waveform, RILEM, Materials and Structures 35 (248) (2002) 198–203.

[4] S. Laurens, J.-P. Balayssac, J. Rhazi, G. Klysz, G. Arliguie, Nondestructive evaluation of concrete moisture by GPR: experimental study and direct modeling, Materials and Structures: Special Concrete Science and Engineering 38 (283) (2005) 827–832.

[5] K. Pokkuluri, Effect of admixtures, chlorides and moisture on dielectric properties of Portland cement concrete in the low microwave frequency range, Thesis for the degree of Master of Science in Civil Engineering, Virginia Polytechnic Institute and State University, 1998.

[6] R.H. Haddad, I.L. Al-Qadi, Characterization of Portland cement concrete using electromagnetic waves over the microwave frequencies, Cement and Concrete Research 28 (10) (1998) 1379–1391.

[7] M.N. Soustos, J.H. Bungey, S.G. Millard, M.R. Shaw, A. Patterson, Dielectric properties of concrete and their influence on radar testing, NDT&E International 34 (2001) 419–425.

[8] G. Klysz, J.-P. Balayssac, S. Laurens, Spectral analysis of radar surface waves for non-destructive evaluation of cover concrete, NDT&E International 37 (3) (April 2004) 221–227.

[9] G.G. Clemena, Short-pulse radar methods, in: Malhotra, Carino (Eds.), CRC Handbook of Non Destructive Testing of Concrete, CRC Press, 1991, pp. 235–294.

[10] D.J. Daniels, Surface-Penetrating Radar, Instit. Electrical Engineers, London, UK, 1996 (300 pp.).

[11] G. Klysz, X. Ferrieres, J.P. Balayssac, S. Laurens, Numerical FDTD model for a GPR coupled antenna, GPR 2004, Delft, Netherlands, June 21–24 2004, pp. 45–48.

[12] A. Berktold, K.G. Wollny, H. Alstetter, Subsurface moisture determination with the ground wave of GPR, Proceedings of the Seventh International Conference on Ground Penetrating Radar, vol. 2, University of Kansas, Lawrence, Kansas, USA, May 27–30 1998, pp. 675–680.

[13] S.J. Radzevicius, Chi-Chih Chen, L. Peters, J.J. Daniels, Near-field dipole radiation dynamics through FDTD modeling, Journal of Applied Geophysics 52 (2003) 75–91.

[14] G. Klysz, X. Ferrieres, J.-P. Balayssac, S. Laurens, Simulation of direct wave propagation by numerical FDTD for a GPR coupled antenna, NDT & E International 39 (4) (June 2006) 338–347.

[15] Z.M. Sbartaï, S. Laurens, J.-P. Balayssac, G. Arliguie, G. Ballivy, Ability of the direct wave of radar ground-coupled antenna for NDT of concrete structures, NDT & E International 39 (5) (July 2006) 400–407.

[16] G. Klysz, Caractérisation du béton d'enrobage par technique radar: exploitation de l'onde directe émetteur-récepteur, Doctoral Thesis, Université Paul Sabatier, Toulouse III, France, 2004.

[17] T. Tillard, J.C. Dubois, Analysis of GPR data: wave propagation speed determination, Journal of Applied Geophysics 33 (1995) 77–91.

[18] J.A. Huisman, C. Sperl, W. Bouten, J.M. Verstraten, Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar, Journal of Hydrology 245 (2001) 48–58.