QUANTITATIVE ULTRASONIC CHARACTERISATION OF CONCRETE DAMAGE USING A MULTIPLE SCATTERING MODEL

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Abstract

The general subject of this study is the non destructive characterisation of concrete damage. Thermal loads on concrete induce the increase of microcracks rate and sizes. The link determination between physical and ultrasonic parameters is possible by effective medium theories which homogenise the physical medium and determine ultrasonic parameters. We studied multiple scattering dynamic models and we adapt the one of Waterman-Truell to the case of damaged concrete. We take into account homogeneous matrix containing air spherical inclusions which simulate damage. Experimentally, we work on cement specimens with aggregates and expanded polystyrene inclusions and measure phase velocity and attenuation. Good agreement is obtained between predicted values and measured ones. A specific behaviour is observed for the velocity: the maximum decrease in velocity amplitude is related to the inclusions rate, and minimum position is tied up to the inclusions size. The experimental velocity evolutions on thermally damaged concrete specimens show similar behaviours.

1. Introduction

There are nowadays a lot of structures, made in concrete material, which suffer variety of constraints imposed by the surrounding conditions. The need to control them is growing and the interest in non destructive techniques is important. In case of thermal loads, the degradation is observed with the microcracks development which are distributed in all the volume with random orientation. The obtained medium is therefore heterogeneous by its composition and by the damage. The thermal loads induce the mechanical properties decrease and the ultrasonic velocity sensibility is shown [1]. The non destructive characterisation is then feasible by ultrasound but, for the moment, the links between physical evolutions and ultrasonic ones are only established by experimental approaches. Most generally, we remark the weak quantities of modelling studies about the ultrasonic wave propagation in concrete.

The principal phenomenon which affects the coherent ultrasonic wave, in concrete material, is the scattering process by the different inclusions [2, 3] and the deficiency of the Born approximation is observed [2]. To improve the wave propagation description, we study a homogenisation model integrating multiple scattering effects. The Waterman-Truell one [4] provides a simple mathematical form to establish the relation between inclusions characteristics and coherent ultrasonic parameters. Experimental validations in a fluid medium have been led, in literature, for spherical scatterers [5, 6]. A solid matrix and other inclusion forms can be considered but no validations were made on them. So, we show that this model can be applied to concrete materials. We present the extension possibilities to reach the final objective: the quantitative characterisation of damage in concrete.

First, we present the multiple scattering model and the different solutions to integrate damaged concrete medium characteristics. Secondly, we propose an experimental set-up that allows us to obtain phase velocity and attenuation in concrete. Thirdly, the comparisons between modelled and measured ultrasonic parameters are made. Finally, we conclude on the progress and the perspectives of this study.

2. Modelling the ultrasonic wave propagation

General principle

The studied model is based on the principle of homogenisation. It allows defining the mean wave which propagates in an homogeneous medium equivalent (marked by an asterisk) to the initial heterogeneous one.

In the virtual medium, called the effective medium, the ultrasonic wave satisfies the well known Helmoltz equation for the plane compressional wave:

$$\left(\nabla^2 + k_\ell^{*2}\right)\left\langle \varphi^* \right\rangle = 0 \qquad (1)$$

where k_l^* is the compressional wavenumber in the effective medium.

The average field has the form

$$\left\langle \varphi^* \right\rangle = \varphi_0^* . e^{i.k_\ell^* . \vec{r}} \qquad (2)$$

where φ_0^* is a constant amplitude value.

The wavenumber in the equivalent medium is related to the phase velocity by the real part and to the attenuation by the imaginary part:

$$k_\ell^* = \frac{\omega}{c_\ell^*} + i.\alpha_\ell^* \qquad (3)$$

Multiple scattering model

The main result of the Waterman-Truell model is the following mathematical relation which expresses the link between the physical parameters and the ultrasonic ones in the effective medium (*):

$$\left(\frac{k_\ell^*}{k_{\ell 1}}\right)^2 = \left[1 + \frac{2.\pi.n_0.f(0)}{k_{\ell 1}^2}\right]^2 - \left[\frac{2.\pi.n_0.f(\pi)}{k_{\ell 1}^2}\right]^2 \qquad (4)$$

where k_{l1} is the compressional wavenumber in the matrix, n_0 is the obstacle density, $f(0)$ and $f(\pi)$ are the forward and backward farfield scattering functions of one obstacle.

This form is valid for a matrix containing several identical inclusions If we have to consider scatterers with different parameters, we can introduce in (4), mean quantity of the scattering functions:

$$\langle f(\theta) \rangle = \int_\alpha p(\alpha).f(\theta,\alpha).d\alpha \qquad (5)$$

where $p(\alpha)$ is the distribution function on α which can be a parameter related to the size, the form, the kind of obstacle or a combination of these.

Simulation in concrete

We simulate the damaged concrete corresponding to the specimens on which the experimental study is made. The considered damage is created by air spherical inclusions which can be representative of the randomly oriented microcracks generated in case of thermal damage.

We choose to introduce, in the concrete matrix, the inclusions by their characteristics, that is to say the density n_0, and the forward $f(0)$ and backward $f(\pi)$ farfield scattering functions. They are calculated for the mean radius by the T-matrix formalism applied to the sphere:

$$f(\theta) = \frac{1}{i.k_{\ell 1}}.\sum_{n=0}^{\infty} (2.n+1).A_n.P_n(\cos\theta) \qquad (6)$$

where P_n is the Legendre polynomial n^{th} order and A_n is called the expansion coefficient defined in [7] and calculated from the matrix and obstacle ultrasonic properties.

3. Experimental set-up

The experimental set-up permits to measure phase velocity and attenuation on concrete specimen and to compare them with the model results.

Measurement chain

The experimental device is composed by a generator, an oscilloscope, a personal computer and three couples of wide band transducers with a nominal frequency of 250 kHz, 500 kHz and 1 MHz. The generator produces an impulsion and the explored frequency domain stretches from 160 kHz to 1.3 MHz. We work in immersion, by wave transmission in the farfield of an emitting transducer.

Comparison measurements method

The chosen comparison method allows to eliminate influence on the measure of the chain elements. We compare (figure 1) two signals which correspond to the wave propagation through the water for the first one and through the specimen and water for the second one.

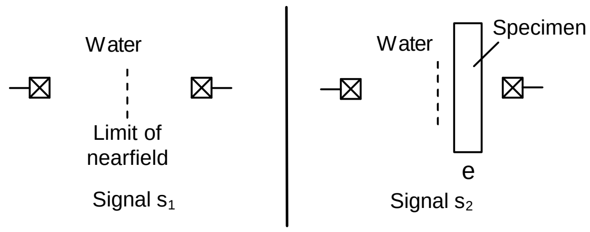

Figure 1 : Comparison method

The frequential analysis allows to determine the phase ($\phi_{c1}(f)$ and $\phi_{c2}(f)$) and amplitude ($A_{c1}(f)$ and $A_{c2}(f)$) of signals s_1 and s_2. Thus, the phase velocity and attenuation are obtained for a given frequency by:

$$\begin{cases} c_\ell = \dfrac{2.\pi.f.e}{\phi_2 - \phi_1 + \dfrac{2.\pi.f.e}{c_w} + \phi_{c1} - \phi_{c2}} & (7) \\[2ex] \alpha_\ell = -\dfrac{1}{e}.\ln\left[\dfrac{A_{c1}}{T_{w/s}.T_{s/w}.A_{c2}}.\dfrac{A_2}{A_1}\right] & (8) \end{cases}$$

where c_w is the phase velocity in water, c1 and c2 are divergence correction coefficients, defined in [8], of respective phases ϕ_{c1} and ϕ_{c2}, of amplitudes A_{c1} and A_{c2}. $T_{w/s}$ and $T_{s/w}$ are the amplitude transmission coefficients at the interfaces water/specimen and vice versa.

Concrete specimens

We explore six cement based specimens presented in table 1.

Table 1 : Specimens formulations

No.	Cement paste	Sand 0.8/1	Gravel 4/8	Expanded Polystyrene	Thermal Treatment
H1	100	-	-	-	-
H2	40	30	30	-	-
SD3	90		-	10	-
SD4	30	30	30	10	-
TD5	100	-	-	-	180°C
TD6	40	30	30	-	180°C

We indicate the volume percent of each component and if the specimen has been thermally treated. We study a pure cement paste (H1) and cement paste with sixty volume percent of granular inclusions (H2). The latter is near to classic concrete formulations. The first studied damage is simulated by air spherical inclusions (SD3 and SD4). The second one consists in temperature elevation over two days up to 180°C, followed by an slow cooling down to the ambient temperature (TD5 and TD6).

4. Comparison theory-experience

Damage simulated by air spherical inclusions

We introduce, in figure 3, experimental velocity and attenuation curves with associated theoretical ones for the cement containing air spherical inclusions.

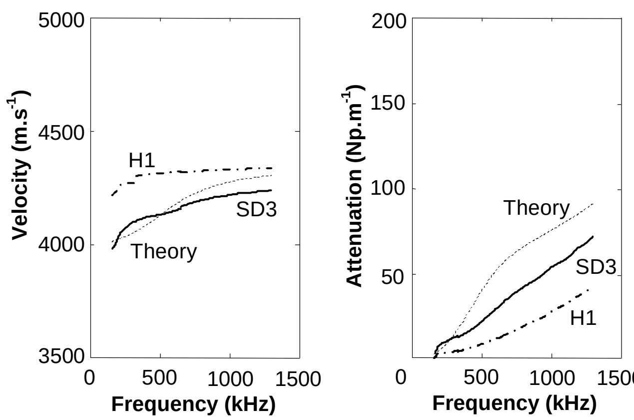

Figure 2 : Ultrasonic velocity and attenuation in pure cement paste with air inclusions

We can observe a velocity decrease and an attenuation increase with the air inclusion introduction in cement matrix. The low frequencies are more affected than the high ones for the velocity and conversely for the attenuation.

We obtain good agreement between the measured velocity and the modelled one for all the frequency domain. We can see a local minimum in velocity, characteristic of the air inclusions size. The modelled attenuation is overvalued for high frequencies

In figure 4, we introduce experimental and theoretical velocity and attenuation curves for the cement containing aggregates and air spherical inclusions.

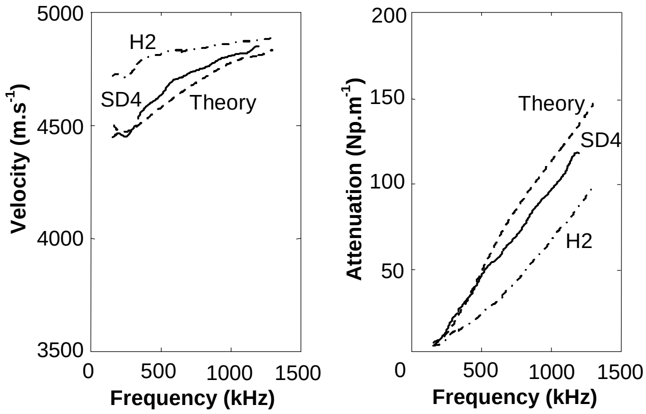

Figure 3 : Ultrasonic velocity and attenuation in cement with aggregate and air inclusions

The same behaviour is observed for the velocity where the local minimum is more marked than before. The good agreement on velocities is also obtained. The absolute values are more important than before due to the presence of aggregates in which the velocity is higher.

The divergence on attenuation is smaller than before and agreement is very good at low frequencies.

Thermal damage

Figure 5 introduces experimental results on velocity and attenuation obtained for thermal damage in cement based materials.

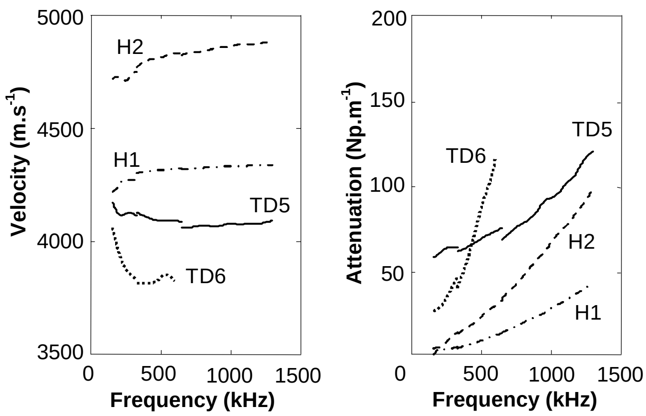

Figure 4 : Ultrasonic velocity and attenuation in thermally damaged cement materials

As before, the damage induces a velocity decrease and an attenuation increase. We can find local minima in velocity curves but less marked than previously and not at the same frequential position. Attenuation curves show high increase when the frequency increases.

For the pure cement paste (curves H1 and TD5), we note a local minimum in velocity but which is not highly marked. On all the frequency domain the effects of air inclusions are observed with similar amplitude.

For the granular medium (curves H2 and TD6), we can first note the reduced frequency domain (max: 600 kHz) due to the high attenuation. A local minimum is observed on velocity and, strong attenuation increase can be enhanced.

We can keep the good agreement obtained on velocity for the simulated damage where we control the air inclusion characteristics.

In case of thermal damage, we keep the same general behaviours with a velocity decrease and an attenuation increase and the presence of local minima in velocity curves. The problem is that we cannot know the exact sizes, forms and volume density of microcracks in the medium to precisely conclude.

5. Conclusion

We studied a multiple scattering model and applied it to cement based materials. In particular, we observed predicted values of velocity and attenuation in case of damaged medium.

For the damage simulated by air spherical inclusions we obtained very good agreement for the velocity on the frequency domain explored. Results in attenuation show good agreement for low frequencies but must be improved for higher ones.

In case of thermal damage we obtain similar behaviours on measured velocities and attenuation. Modelling this medium is not possible, for the moment, due to the lack of knowledge about real scatterers that microcracks are. Certainly, integrated random oriented spheroids instead of spheres in the model will provide theoretical results close to the measured ones.

Acknowledgement

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