Improvement in the Analysis of the Wave's Propagation in Concrete

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Abstract. The topic of the work is to understand the interaction of an ultrasonic wave in concrete or in granular materials. This wave's propagation is currently used to analyse qualitatively and quantitatively the evolution of concrete. Analyses or processing are tested to measure the influence of the microstructure evolution on the wave's velocity or attenuation. Works were developed to model the problem. In order to better understand the physical phenomenon, we propose to observe the propagation of the ultrasonic wave in concrete and to analyse each wave part generated by the interactions with the different obstacles included in concrete. So, it is possible to consider the coherent transmitted wave, the incoherent transmitted wave and the backscattered wave. We define the different interactions and present solutions to measure and model these contributions. We focus on the coherent waves and the homogenisation of the material. We show the interest to adapt a dynamic model for concrete. We establish a link between air inclusions in the medium and the velocity and the attenuation of ultrasound. The experimental results for cement and concrete specimens including polystyrene balls are compared with the calculations. The phase velocity behaviours modelling in relation with the wave frequency, the size and the volume rate of balls present in the medium, validate the model. The extension to the case of real medium must be realised by introducing inclusions geometry near to the real shape of granulates or microcracks in the model. We propose the last experimental and theoretical evolutions developed for this topic.

1. Introduction

The civil engineering control of structures offers to determine a large number of parameters that can be chemical, mechanical or micro-macro structural.
Non Destructive Testing has often been exploited with statistical principles based on correlations between indicators from techniques, and mechanical measures or observations.
To take advantage of these data, the knowledge and command of these techniques used to collect the indicators in laboratory and finally in situ, must be done experimentally and analytically. The developments of direct problem models allow to simulate the information recorded by test and even to consider the inversion. It is important that these models and their limits are validated experimentally in their applications.
In the case of testing by ultrasonic wave's propagation, we develop a homogenisation model proposed by Waterman and Truell [1] for the application on the concrete. We focus particularly on the concrete damage and its influence on the propagation velocity and attenuation of the waves. This damage, studied by P.E. Grattan-bellew [2] among others, induces an evolution of microcracks rate then modifications of the concrete's components with the temperature increase suffered. E. Ringot [3] shows the damage influence on the density, the distribution, the connection as well as the roughness of the microcracks.

The damage state evaluation of concrete will thus depend on this set of data. Let us note that the increase of other parameters like the humidity rate, carbonation or chlorination of concrete develop more quickly with the importance of the microcracks and porosity network that allows the penetration of water and carbon or chlorine. Through the modelling proposed, we present the study of the damage by microcracks and the study of a typical concrete, supposing the other parameters are under control. We will present more particularly the attenuation results.

2. Waves propagation

The waves propagating in the concrete are affected by the geometrical divergence due to the beam's morphology, by the dispersion generating heat as well as the diffusion by interaction with the sand grains, microcracks, cracks and even reinforcement bars.
According to the wave's length λ compared with the scatterers' diameter a, the interactions could be arranged in three domains: first is the Rayleigh domain with $\lambda >> a$, second is the stochastic domain with $\lambda \approx a$, third is the geometric domain $\lambda << a$. The case of concrete with waves' lengths used from 5 mm to 100 mm, is in the stochastic domain in which the diffusion phenomena could be very important.
If we limit the analysis to the waves' diffusion that modifies the velocity and attenuation of the waves in space, the energy of the beam can be transferred into coherent transmitted waves, incoherent transmitted waves as well as backscattered waves.
The separation between the coherent waves that keep the phase with the initial wave and the incoherent wave that loses this phase can be illustrated with figure 1. The length on which the coherent wave dies down corresponds to the mean free path l of the wave [4].

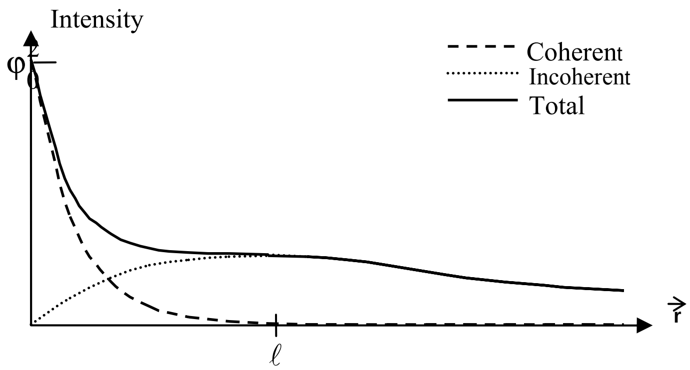

Figure 1: Separation of the coherent and incoherent waves

Concerning the works on the concrete, the incoherent part known as "coda" can be analysed by different methods. The diffusion constant of the wave's intensity in the material can be calculated [5].
In the backscattered part, the multidiffusion presence is displayed on a wall for a low frequency [6]. The backscattered waves are related to the porosity rate of a cement paste [7] by the analysis of the back diffusion cone. They can also be correlated with thermal damage of concrete [8].
The coherent part that is the aim of this work is often based on statistical analysis that leads to the material homogenisation. The general principle, shown on figure 2, consists in determining an "equivalent" material with acoustical properties "equivalent" to those of the

heterogeneous material constituted of several materials with known characteristics, geometry and dimensions. The rate of each constituent in the matrix is known.

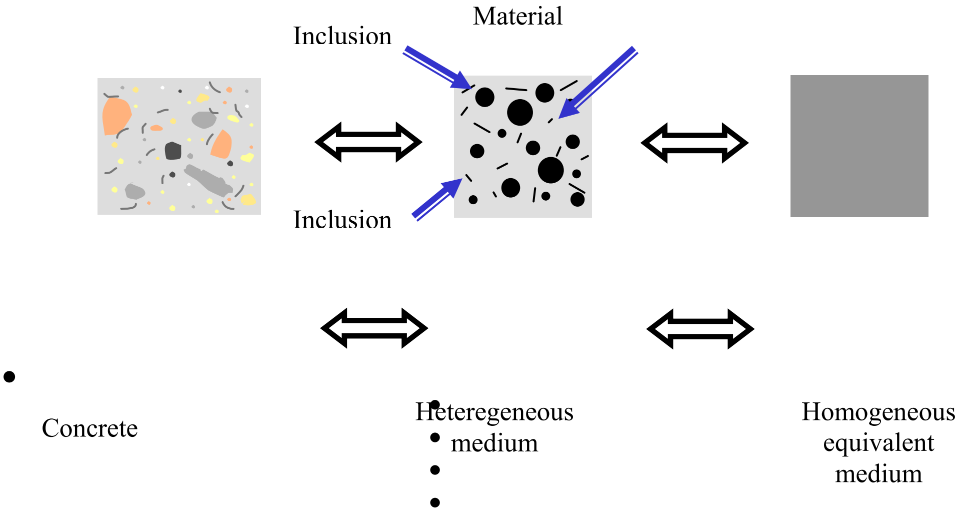

Figure 2 : Principle of homogeneisation

2.1 Multidiffusion

The physical phenomenon of the diffusion that corresponds to the interaction of a wave with a scatterer can be applied one time or several times. The principle is presented in figure 3. The wave interferes with a scatterer. The diffused part can interfere with another scatterer. The new diffused part can repeat the phenomenon.

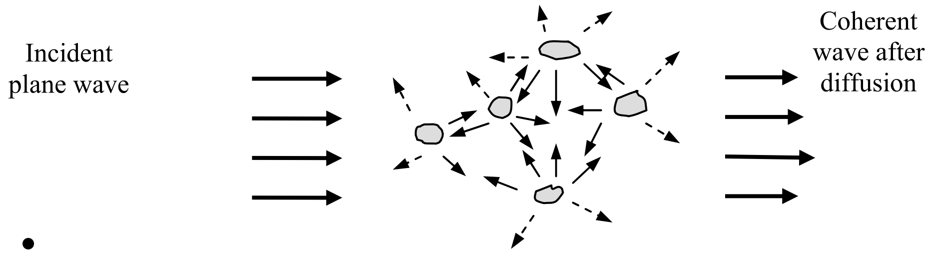

Figure 3 : Multidiffusion principle

The models developed on the simple diffusion principle show their validity limits [9] on the scatterers' rates included in the material as well as on the frequency bandwidth of the waves exploited. Taking into account the multiple diffusion is essential to explain the comportments of the waves in the case of stochastic propagation. Models based on works of Lax [10] or Foldy[11] were developed in different mediums. Manou [12] compares the model developed by Watermann Truell [1] or Linton and Martin [13] with the Independent Scattering Approximation for cylindrical scatterers in water. There are few applications of this type of model on concrete [14].

2.2 Application to the case of concrete

The work consists in verifying the applicability of the Watermann Truell model to the case of a concrete thermal damage [15]. We focus in the first place on the simulation of the damage by introducing air spherical scatterers and thereafter on the simulation of the material with rock spheres in the cement matrix.

2.2.1 Modelling

This homogenisation model takes into account mean scatterers. The mean field of the wave is given by:

$$\langle \varphi \rangle = \varphi_0 . e^{i.k^*.\vec{r}} \tag{1}$$

with φ_0 a constant, $\vec{r}$ the observation position and k^* the equivalent wave number of the compression wave . k^* is given by

$$k^* = \frac{\omega}{C_p^*} + i.\alpha^* \tag{2}$$

With C_p^* the phase velocity and α^* the attenuation of the wave as a function of the frequency in the equivalent material.
k^* is deduced from the wave number knowledge in the matrix k_l . The formalism was proposed by Watermann Truell in the case of n_0 identical spherical scatterers.

$$\left(\frac{k^*}{k_1}\right)^2 = \left[1 + \frac{2.\pi.n_0.f(0)}{k_1{}^2}\right]^2 - \left[\frac{2.\pi.n_0.f(\pi)}{k_1{}^2}\right]^2 \tag{3}$$

The amplitude function is calculated according to the observation angle θ with a specific operator " T-matrix" and nth order Legendre's polynomials P_n^0.

$$f_\ell(\theta) = \frac{1}{i.k_{\ell 1}} . \sum_{n=0}^{\infty} (2.n+1) . T_{n0n0}^{11} . P_n^0(\cos\theta) \tag{4}$$

where f(0) et f(π) are the waves amplitudes diffused forward or backward by an obstacle.

In the case of several types of scatterers, it is possible to take into account their characteristics under the form of mean quantities.

$$\langle f_\ell(\theta) \rangle - \int_\alpha p(\alpha).f_\ell(\theta,\alpha).d\alpha$$

where $p(\alpha)$.is the distribution function of the parameter α characteristic of the size, or the shape, or the obstacle type or a combination of some of them.
If the material is concrete, we introduce a set of rock spheres with the same size so as to simulate a set of aggregates with corresponding mean size and geometry.
If we analyse the concrete damage, it is necessary to model the cracks and microcracks. Today, it is not possible to take into account the particular morphology of the cracks. The thermal damage that we are studying is isotropic. So we assume that a set of cracks or microcracks full of air and oriented randomly in space generates interactions with the compression wave equivalent to the ones generated by a set of identical air balls with a judiciously chosen diameter. Thus we simulate the presence of microcracks by expanded polystyrene balls with a 2.84 mm diameter as shown on figure 4.

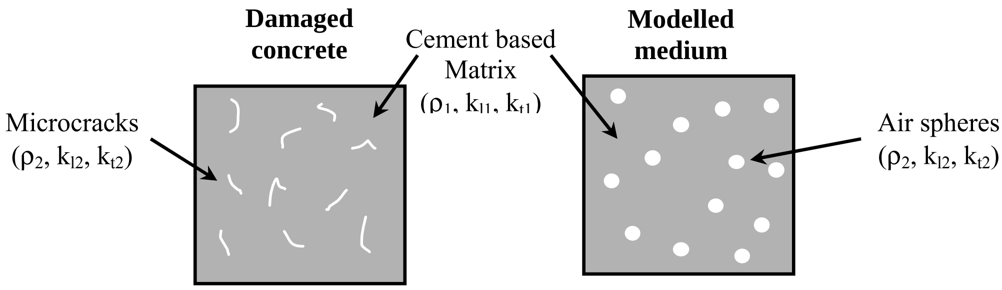

Figure 4: Cracks modelling

3. Experimentation

3.1.Principle

The experimentation has been realised in immersion with water saturated specimens in order to ignore this parameter that strongly influences the results. The measure is carried out as seen on figure 5, by comparison between the signal crossing the water, and the one crossing the water and the specimen with a thickness e.

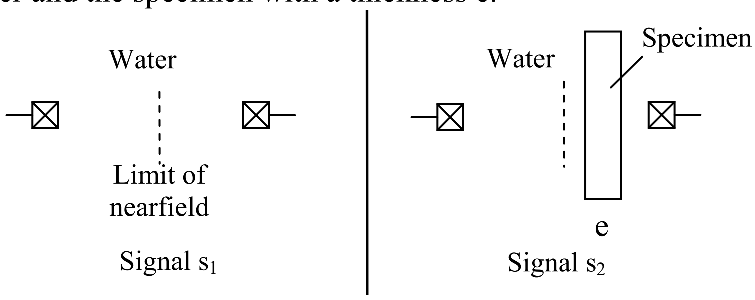

Figure 5: Measurement by comparison

The frequencies analysis allows to determine the phases ($\phi_1(f)$ and $\phi_2(f)$) and amplitudes ($A_1(f)$ and $A_2(f)$) of signals s_1 and s_2. Thus, the phase velocity c(f) and attenuation $\alpha(f)$ are obtained for a given frequency by:

$$c(f) = \frac{2.\pi.f.e}{\phi_2(f) - \phi_1(f) + \frac{2.\pi.f.e}{c_w} + \phi_{D1}(f) - \phi_{D2}(f)} \tag{7}$$

$$\alpha(f) = -\frac{1}{e}.\ln\left[\frac{D_1(f)}{T_{w/s}(f).T_{s/w}(f).D_2(f)}.\frac{A_2(f)}{A_1(f)}\right] \tag{8}$$

where c_w is the phase velocity in water and $T_{w/s}(f)$ and $T_{s/w}(f)$ are the coefficients of amplitude transmission at the water/specimen and specimen/water interfaces. $D_1(f)$, $D_2(f)$ and $\phi_{D1}(f)$, $\phi_{D2}(f)$ are respectively the amplitudes and the phases of beam divergence correction coefficients defined in [16].

3.2 Results

3.2.1. Damage

For Chaix [15], the details of calculations, experimentations and results present the influence of the size and the density of the balls on the velocity and attenuation in theoretical and practical configurations. It is interesting to keep the case of a material closer to the concrete and that represents the set of evolutions analysed. The tests result from spatial averages in order to take into account the random distribution of scatterers. The specimens are cylinders with a 250 mm diameter and a 45 mm length.
The constitution of the undamaged (sound) specimen is 40 % of cement paste, 30 % of 0.8/1 mm fine sand and 30 % of 5/6.3 mm granulates. In the damaged specimen, 10 % of 2.8 mm polystyrene balls replace 10 % of cement paste.
The experimental results of the phase velocity and attenuation are compared with those calculated on figure 5.

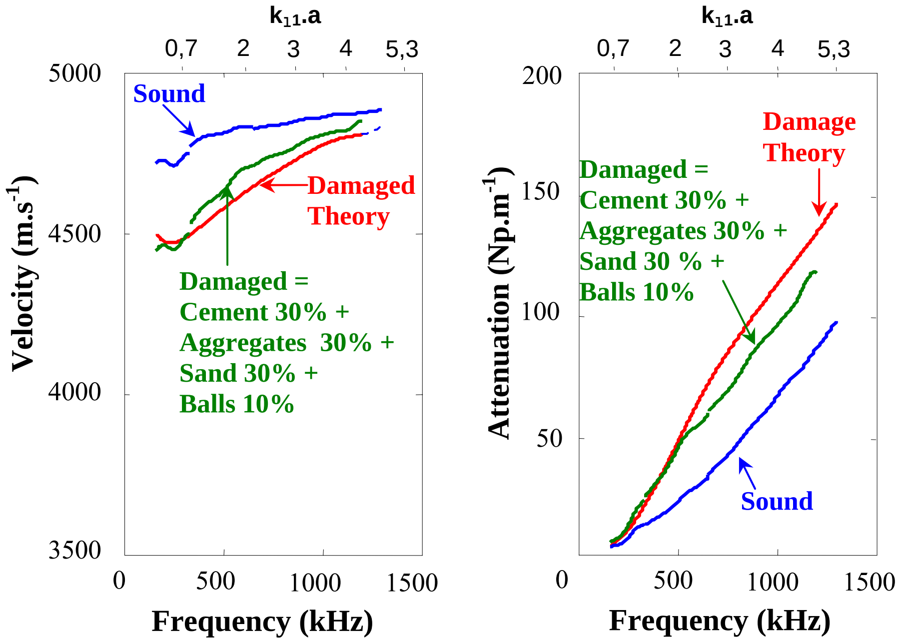

Figure 5: Theoretical and experimental ultrasonic velocity and attenuation as a function of frequency for the undamaged specimen: Cement paste 40%, Sand 30 %, aggregates 30 %, Balls 0 % and for the damaged specimen: Cement paste 30%, Sand 30 %, aggregates 30 %, Balls 10 %

The experimental values of the velocity and attenuation of the sound specimen are taken as reference for the global matrix in the case of the damaged specimen calculations.
These comparisons show a theoretical description very close to the real evolutions of the velocity in the case of the artificially damaged specimen. The curve's minimum is plotted for a value of k.a close to 0.5 that places our test in the stochastic domain. Concerning the attenuation evolutions, the conformity is not so relevant for frequencies over 500 kHz that corresponds to a value of k.a close to 1. The attenuation relative gaps are more important than the velocity ones. These differences can be explained by the methodology of the diffusion functions calculations. We do not take into account the contribution of the waves that suffer changes of modes, namely the pressure waves that convert into shear waves and convert back into pressure waves. We suppose their influence to be unimportant because they are late regarding the analysed coherent waves. However, when the wave length increases with the frequency and tends to get small as compared to the scatterers' size, the refraction phenomenon can be prominent over the diffusion one. In this way, the energy

transferred into shear waves can increase and the attenuation calculated by our application can be overestimated.

3.2.2. Material

This part of the work concerns a concrete with 70 % of cement past and 30% of granulates. The objective is to simulate the propagation of the waves in the concrete and to do the comparison with the experiment. The theoretical granulates are spheres 5.65 mm in diameter. We work with two hypotheses. The first is a unique size of aggregates and the second is a distribution of their sizes with a standard deviation σ of 0.394 mm. Figure 6 shows the results. The experimental values of the velocity and attenuation of the cement paste are the references and are taken as values for the cement matrix in the specimen calculations of the simulated concrete.
The results analysis shows that velocity simulations do not allow to describe the wave's velocity as a function of the frequency. The gaps are consequent. The introduction of the sizes' distribution on the basis of the mean value and standard deviation defined, induces a fall in the curve and an increase in the difference between theory and experimentation. We can also observe a shift of the velocity maximum towards lower frequencies. The k.a value is around 1.5 for the theoretical curve and 4.5 for the experimental one.

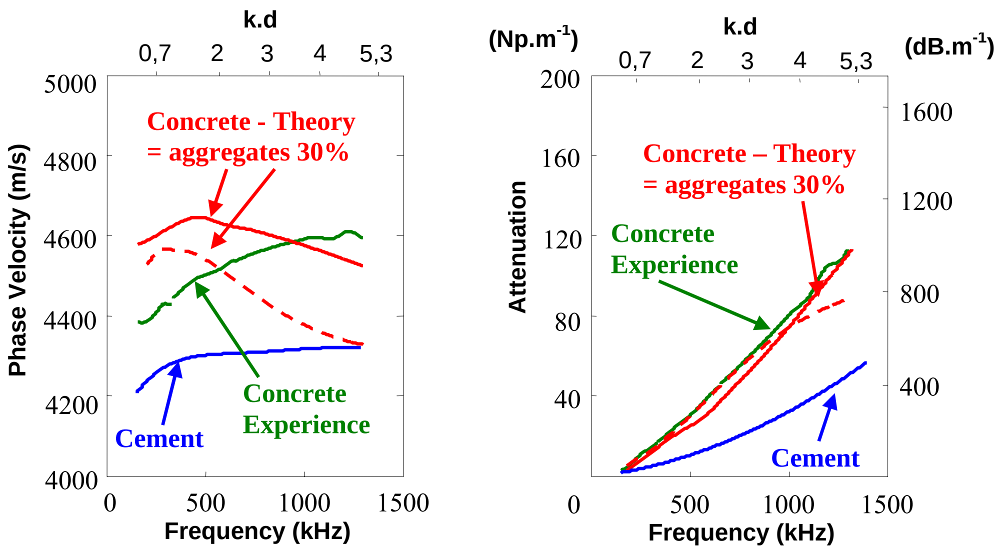

Figure 6: Theoretical and experimental ultrasonic velocity and attenuation as a function of frequency
for cement: Cement paste 100%, Aggregates 0 %
and for concrete: Cement paste 70%, Aggregates 30 % (mean value = full line; size distribution = dotted line)

Some hypotheses can be proposed to explain the differences. First, in the interaction, a part of the wave goes around the scatterer and the other part through the scatterer itself. The modelling could describe the distribution of the incident wave's energy into the two components inaccurately. Second, the aggregates' roughness disrupts the diffusion phenomenon. Third, the influence of aggregates' morphology is important. We are now working on the introduction of spheroid aggregates in the concrete modelling.
Conversely, the calculated description of the attenuation as a function of the frequency is in very good agreement with the measured values. In addition, the aggregates size distribution does not modify the attenuation curve.
We can retain currently that even if the velocity is difficult to describe by the Waterman Truell model, the attenuation is well calculated for our case. It is very interesting to be able to describe the attenuation in order to predict the signal's measurable amplitude of a wave that has followed a known path in a known concrete.

4. Conclusion

Non Destructive Testing gives the measure of an amplitude or time of flight of a single signal or a composition of signals. The data carried by a transmitted wave through a concrete specimen or structure can get complex and be distributed in space forward or backward. Moreover it can be out of phase. The homogenisation approach has been tested in a laboratory context that makes the separation and understanding of information easier. The comparison between theory and experimentation shows good results. Some difficulties still have to be resolved.

The on site industrial techniques of Non Destructive Testing by ultrasounds, that are the objectives of these works, are based on the same type of measurements data. A step of modelling and models' improvement or models' optimisation techniques can allow to improve the diagnosis. Namely the measurements of the attenuation and velocity dispersion curve are in progress. It is in this context that we continue this first step. We want to describe both the physical phenomenon and the material in a more realistic way. Presently, we are working on diffusion by spheroid scatterers.

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