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Ultrasonic Wave Dispersion and Attenuation in Fresh Cementitious Materials

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Abstract

In this work, the dispersive and attenuative behavior of fresh cementitious materials is examined through a series of ultrasonic Pulse-Echo measurements using the prism technique. Measurements were carried out using prism shaped specimens for different Water Cement Ratios within a short period after mixing.

Both pressure and shear waves are generated by mode conversion in a prism-shaped specimens, and to better understand this method, a numerical model based on the Finite Difference in Time Domain has been developed that simulates the elastic wave propagation in the specimen.

Theoretical analysis seems to explain the observed dispersion and attenuation mainly through two scattering interactions: sand embedded in paste and air bubbles in mortar.

Several snapshots were generated to get more information on the relationship between dispersion effect and the propagation velocities.

Résumé

Dans cet article, la dispersion et l'atténuation des matériaux cimentaires frais sont étudiées à l'aide de plusieurs mesures ultrasonores par la méthode Pulse-Echo, avec la technique de Prisme.

Ces mesures ont été effectuées par des spécimens en forme de prisme pour différentes valeurs du rapport Eau/Ciment dans un bref délai après le mélange.

Les deux ondes, l'onde de pression et l'onde de cisaillement sont générées par conversion dans l'échantillon. Pour mieux comprendre cette méthode, un modèle numérique basé sur la méthode des Différences Finies dans le Domaine Temporel a été employé.

L'analyse théorique explique la dispersion et l'atténuation observées par défraction dues au sable et aux bulles d'air dans le mortier.

Plusieurs instantanés ont été générés pour donner plus d'informations sur la relation entre la dispersion et la vitesse de propagation.

Keywords:

Cementitious materials, ultrasound testing, dispersion, attenuation, FDTD.

1 Introduction

The methods based on ultrasound are better suited for the characterization of the setting and hardening of cement based materials than traditional methods, because the travel time, the attenuation and frequency content of ultrasonic waves sent through the material are closely correlated with the elastic properties of concrete or mortar [1]. These parameters can be closely monitored during the stiffening of the material. There exist many testing methods based on pulse-transmission, pulse-echo, impact-echo, and resonance techniques [1,3]. The strength of cementitious materials increases with age and it is thus important to predict its value at any given stage of a construction process. Many investigations have shown a correlation between the increase of the speed of ultrasound and the increase of equivalent strength of cementitious materials with age [1,3].

In this paper, we propose a recent immersion technique for testing based on Prism-Shaped specimen. Both pressure (P) and shear (S) waves are generated by mode conversion in a Prism-Shaped specimen, and to better understand this method, a numerical model based on the Finite Difference Time Domain (FDTD) has been developed that simulates the elastic wave propagation in the specimen.

2 Basic principles of the prism technique

The main piece of the apparatus is the transducer cell shown in Fig.1. It consists of a water tank in which the specimen under test (SUT) is fixed. The single transducer that acts as both transmitter and receiver is put on a circle that turns around SUT with a radius *R* (about 4 Cm). The ultrasonic beam makes an angle θ, that varies in a continuous manner from 0° to 90°. The main face of SUT is put against the diameter line XX' and has to be placed in such a way that its center coincides with the center of the transducer circle. This is done by moving SUT parallel to XX' following the arrows and pointing the right angle of the prism in the direction of the positioning line. The latter is perpendicular to the main prism surface.

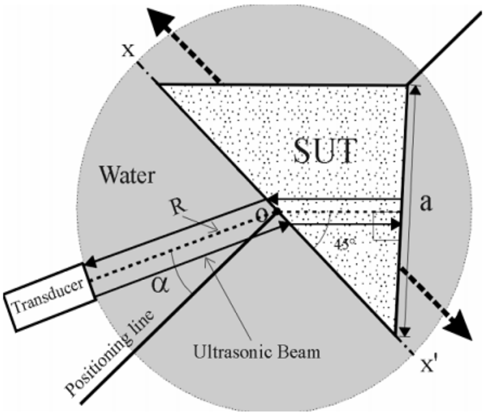


Figure 1. *Transducer cell configuration as used for the prism technique.*

The key idea of the prism technique is that only waves inside the prism with a refraction angle of 45° significantly contribute to the sensor signal. These refracted waves impinge normally on one of the side faces of the prism with length (*a*), are reflected at the Prism/Water interface, and propagate back to the receiver using exactly the same travel path as before. The longitudinal and transverse waves are given by:

$$V_l = \sqrt{\frac{\lambda+2\mu}{\rho}} \qquad (2)$$

$$V_s = \sqrt{\frac{\lambda}{\rho}} \qquad (3)$$

While λ and μ are the Lamé constants, and ρ is the material density.

The percentage of incident energy reflected from the interface between two materials depends on the ratio of acoustic impedances and the angle of incidence.

At Water/Specimen interface the wave reflection and transmission coefficient are given by the flowing equations [2]:

$$Tl = \left(\frac{\rho_f}{\rho_s}\right)\frac{2Z_l\cos(2\theta_s)}{Z_l\cos^2(2\theta_s) + Zs\sin^2(2\theta_s) + Z_f} \qquad (4)$$

$$Ts = -\left(\frac{\rho_f}{\rho_s}\right)\frac{2Z_s\sin(2\theta_s)}{Z_l\cos^2(2\theta_s)+Z_s\sin^2(2\theta_s)+Z_f} \tag{5}$$

Where

$$Zl = \frac{\rho_s V_l}{\cos\theta_l},\ Zs = \frac{\rho_s V_s}{\cos\theta_s} \text{ and } Zf = \frac{\rho_f V_f}{\cos\theta_f}$$

Whereas θ_f is the angle of incidence/reflected wave in the liquid, and θ_l, θ_s are the angles of refracted longitudinal and shear wave in the solid, respectively, and V_f, V_s and V_l are the wave speeds of the longitudinal wave in the liquid and of the shear and longitudinal wave in the solid, respectively.

In order to discuss the formulae, we choose an elastic half space with $\rho_s = 2133 Kg/m^3, V_l = 2750\ m/s, V_s = 1470 m/s$, according to a typical mortar specimen with water/cement ratio 0.35, and $\rho_f = 1000\, Kg/m^3$ and $V_f = 1470\, m/s$.

The directions of the reflected and transmitted waves are determined by Snell's law. Mathematically, Snell's law can be expressed as:

$$\frac{\sin\theta_f}{V_f} = \frac{\sin\theta_s}{V_s} = \frac{\sin\theta_l}{V_l} \tag{6}$$

At increasing angle of incidence, $\theta_i > 0$, an additional shear wave with increasing intensity is generated in the specimen by mode conversion of the incident *P* wave, at θ_1 the *P* wave disappears from the specimen. This first critical angle is given by:

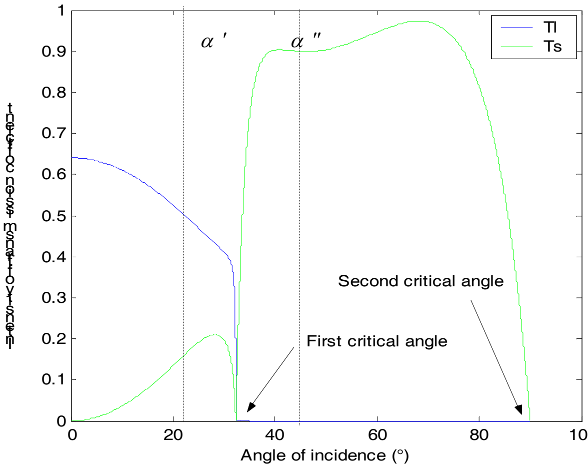
$$\theta_1 = \arcsin\left(\frac{V_f}{V_l}\right) \tag{7}$$

In the solid for $\theta_i > \theta_1$, the incident *P* wave is completely transformed into the mode converted *S* wave. This second critical angle of incidence is given by:

$$\theta_2 = \arcsin\left(\frac{V_f}{V_s}\right) \tag{8}$$

In our present example this happens at $\theta_1 = 32{,}3°$ and $\theta_2 = 90°$.

From Equ.6, to find the refraction angle of 45°, this happens if the angle of incidence is: $\theta' = \arcsin\left(\frac{1}{\sqrt{2}}\frac{V_f}{V_p}\right)$, for the refracted *P* wave, and $\theta'' = \arcsin\left(\frac{1}{\sqrt{2}}\frac{V_f}{V_s}\right)$, for the mode converted *S* wave. For our example we obtain $\theta' = 22{,}2°$ and $\theta'' = 45°$.



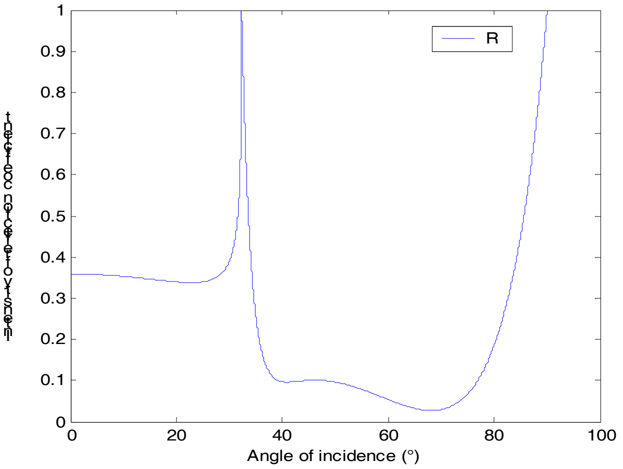


Figure 2. *Intensity reflection coefficient, R, transmission coefficient for the refracted L wave, T_l, and transmission coefficient for the mode converted S wave, T_S*

3 Simulation study

The source signal used in this work, is expressed by:

$$x(t)=\cos\left(w*n*fr\right)*\exp\left(\frac{-a\left(t_0-n\right)}{B}\right)^2 \tag{9}$$

Where $w=2*\pi*f$, *fr:* is the relative frequency of ultrasonic transducer, *B*: its bandwidth and a : constant equal 1. Let us take as example $f=1MHz,\ fr=1, B=10^{-6}s$

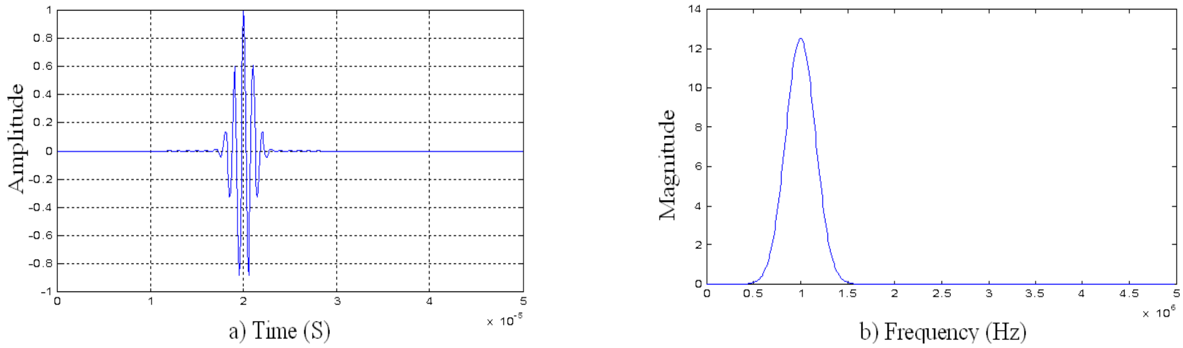


Figure 3. *Signal source, a) Test Signal b) Its spectrum*

The numerical model for solving the system stress-strain [2] is based on the Finite Difference in Time Domain method, the Courant stability condition (CLF) must be satisfied when the method is used. The stress-strain system is given by:

$$\begin{cases}\dfrac{\partial T}{\partial t}=\overline{C}\nabla v\\[2mm] \dfrac{\partial v}{\partial t}=\dfrac{1}{\rho}\nabla .T\end{cases} \tag{10}$$

Where $T=\lfloor T_1\ \ T_2\ \ T_3\ \ T_4\ \ T_5\ \ T_6\rfloor$ is the velocity vector, $v=\left[v_1\ \ v_2\ \ v_3\right]^T$ is the stress vector, $\overline{C}$ is the piezoelectric elastic constant matrix.

We limit our analysis to two dimensions by setting spatial derivative with respect to *y* to zero[2].

The determination of the elastic constants of material is then based on the following three steps. At the start, we measure the transit time of reflected *P* wave at a normal incidence α_i is set to zero Fig.4.a, it enables the evaluation of the time of flight t_{of} by using the formula $t_{of}=\dfrac{2R}{v_f}$. After that, the angle is increased until the appearance of a second echo Fig.4.b, which is related to compressional waves. It coincides with the first critical angle which gives rise to a refracted compressional wave at an angle of 45°within SUT. Because the wave impinges at an angle of 90° on the second face it gets totally reflected due to the impedance mismatch between SUT and the water, and thus the beam follows the same path in its way back to the transducer. This enables the evaluation of *Tc*, the time of flight reflected *P* wave. The angle is increased further, until the second critical angle is reached which gives rise to a third echo Fig.4.c that enables the evaluation of *Ts,* the time of flight of the mode converted S wave. Then the velocity of ultrasonic waves is evaluated from the following simple formula: $v_{c,s} = \dfrac{a}{T_{c,s} - t_{of}}$, where a, represents the side of the prism, then elastic constants of a specimen are calculated from very well know formulae: $\lambda = \rho\left(v_c^2 - 2v_s^2\right)$, $\mu = \rho v_s^2$, $E = \dfrac{\rho v_s^2\left(3v_c^2 - 4v_s^2\right)}{v_c^2 - v_s^2}$, $K = \dfrac{\rho v_s^2\left(3v_c^2 - 4v_s^2\right)}{3}$ and $\sigma = \dfrac{v_c^2 - 2v_s^2}{2\left(v_c^2 - v_s^2\right)}$.

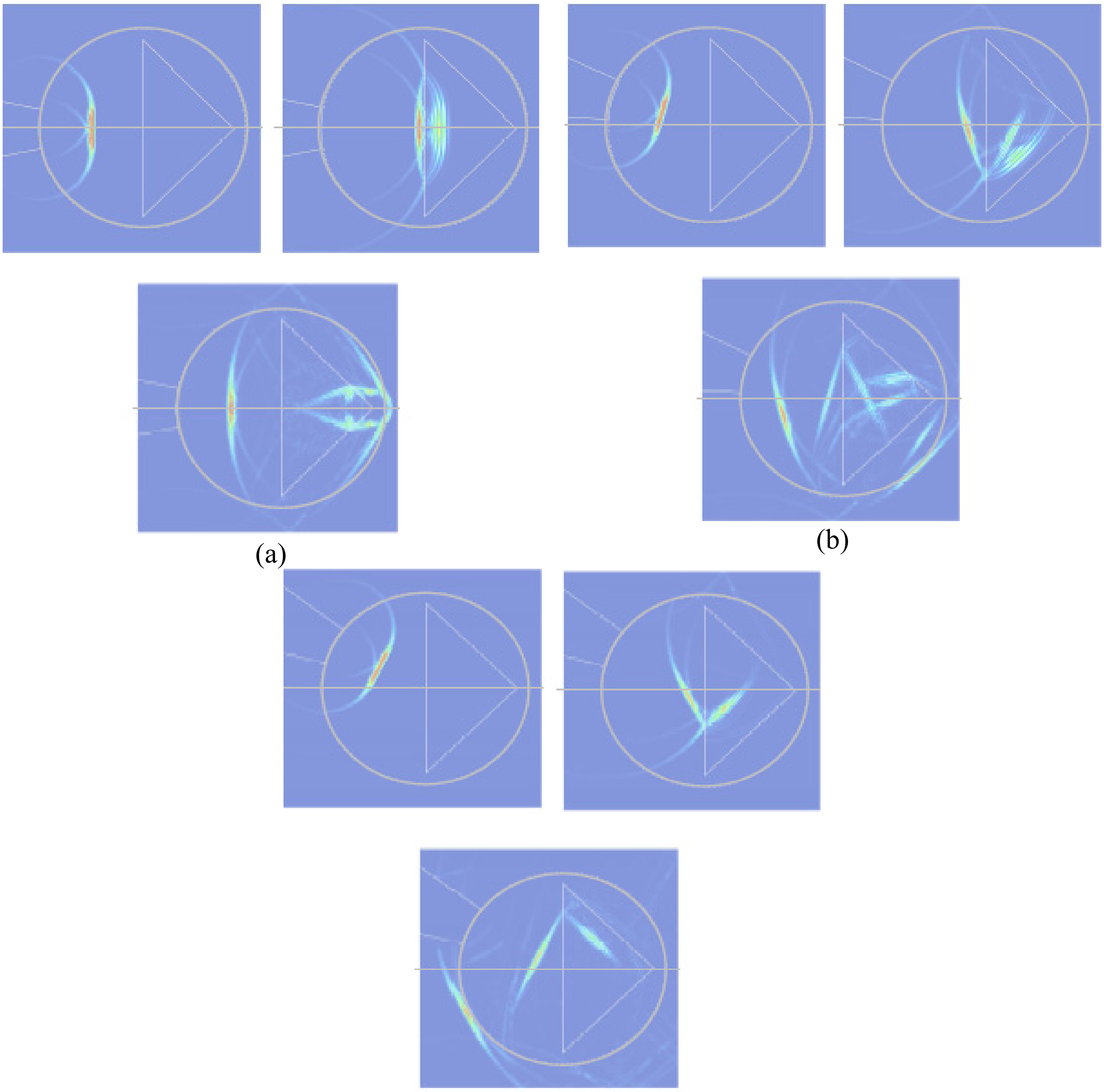

(a)
(b)
(c)

Figure 4. *2-D FDTD simulation, a) of a normal incidence, b) for a L wave, c) for the mode converted S wave.*

4 Experimental procedure and measurements of v_s by mode conversion

The schematic of the ultrasonic measurement consists of various elements which are depicted in Fig.5. It consists of an Ultrasonic Pulser/Receiver, an Immersion Transducer (Panametrics, 1 MHz), a Digital Oscilloscope (Tektronix TDS 1002), a PC with WaveStar software for data-acquisition.

The transducer is connected to the hardware as shown in Fig. 5, so that the first measurement can be taken few minutes after mixing of the mortar.

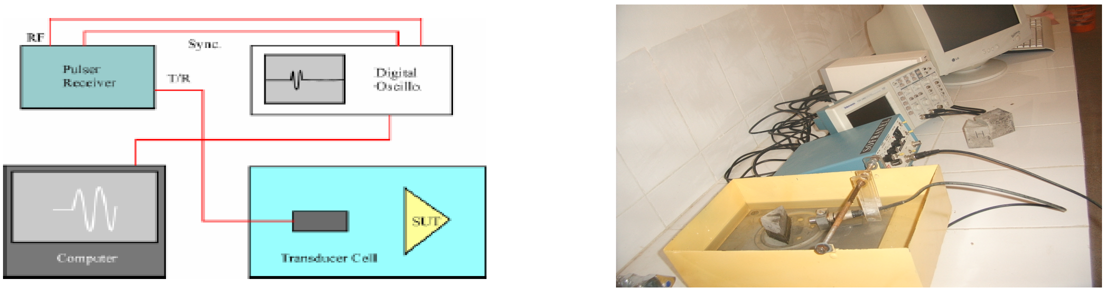


Figure 5. *Schematic diagram (Left) and photograph of the ultrasonic apparatus (Right).*

5 Dispersion and attenuation

In Fig. 6, the velocity v_s frequency curve of material with different sand contents SA; is depicted, this velocity staying approximately constant for higher frequencies. The variation in w/c ratio seems to have a slight influence on the dispersion curve as can be seen in Fig.6. To fits the data we have used many polynomials of degree ten.

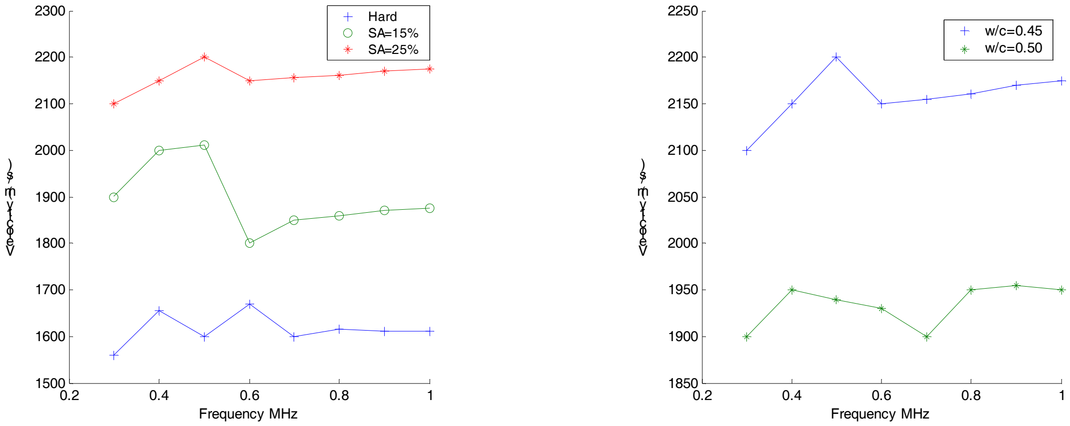


Figure 6. *Left) Effect of sand content on dispersion curves w/c=0.45 specimen, right) Effect of w/c ratio on dispersion curves with SA=24%.*

6 Conclusions

The objectives of this paper are: first, the study of wave propagation in fresh cementitious materials by using Prism technique, it enables the evaluation of wave velocities with relative ease. Second, the simulation results using FDTD show an agreement with the experimental ones related to various parameters like velocities. In this technique there is just one transducer used for measuring the wave velocity of both compressional and shear waves. Third, experiment has shown clearly that, sand content and w/c ratio affecting both velocity and attenuation in specimen.

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