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Application of Waterman-Truell and the Dynamic Generalized Self-consistent Models on Concrete

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Abstract

Acoustic wave propagation in heterogeneous and dispersive media is a very complex phenomenon, where the phase velocity and attenuation are function of the material microstructure, and becomes frequency-dependent parameters. In this paper, the interaction between ultrasound waves and cement-paste specimens have been analyzed by two multiple scattering models, based on homogenization approach, and experimental data. The experimental phase velocity, attenuation and the dispersion results show good agreement with the theoretical models; the experimental phase velocity and attenuation decrease for higher w/c ratio, as predicted by the theoretical models.

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1. Introduction

The mechanical, physical and durability properties of concrete directly depend on concrete porous structure and, especially, on the microstructure of the hydrated cement paste, the glue of this multi-phase material. It has been established that the density as well as the elastic modulus are correlated to ultrasonic velocity. These factors are meanly determined respect to the water to cement (w/c) and hydration ratios, for that matter, theoretical and experimental analysis must carried out to correlate the porosity of the cement-paste with the phase velocity and attenuation of the ultrasonic wave, traveling throughout this heterogeneous and dispersive media. Several multiple-scattering theories have been developed where the homogenization approach expresses the longitudinal and stress acoustic potentials as function of the wavenumbers. The latters are related to the microstructure, phase velocity and attenuation. The experimental counterpart was carried out using through-transmission ultrasound on 18 cement-paste controlled blocks with different w/c ratios.

2. Theory

Acoustic wave propagation through a media with randomly distributed inclusions undergoes multiple scattering, which results in a frequency-dependent phase velocity and attenuation of the coherent wave. There are several methods

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to analyze multiple scattering phenomena, among them is the homogenization process, where each heterogeneous medium appear as a dissipative homogeneous material, and the propagation is governed by complex effective wave number, where the real part represents the phase velocity and the imaginary is related to the attenuation of the wave. The effective elastic properties of a homogenized two-phase system compose of randomly distributed spherical-shaped inclusions surrounded by fluid media can be computed by two homogenization approaches: the Waterman-Truell theory (WT) Waterman (1961) and the Dynamic Generalized Self-Consistent Model (DGSCM) Yang (2003).

2.1. Waterman-Truell Theory

The Waterman-Truell model considers the total scattered field as a superposition of all interactions between the wave and the inclusions in the fluid-matrix (effective medium), the longitudinal and shear acoustic potentials are defined in Bose (1974), where complex longitudinal and shear wavenumbers (k and K),in a 'two-phase homogenized medium', are defined as

$$\left|\frac{k}{k_m}\right|^2 = \left[1 + \frac{2\pi n_0 f(0)}{k_m^2}\right]^2 - \left[\frac{2\pi n_0 f(\pi)}{k_m^2}\right]^2 \tag{1}$$

$$\left|\frac{K}{K_m}\right|^2 = \left[1 + \frac{2\pi n_0 g(0)}{K_m^2}\right]^2 - \left[\frac{2\pi n_0 g(\pi)}{K_m^2}\right]^2 \tag{2}$$

where c is the inclusions volume fraction, $f(0)$ and $f(\pi)$, $g(0)$ and $g(\pi)$ are the forward, backward longitudinal and shear scattered waves amplitudes by a single inclusion of radius a, respectively, given by

$$f(0) = \frac{1}{ik_1}\sum_{n=0}^{\infty}(2n+1)a_n^* \qquad f(\pi) = \frac{1}{ik_1}\sum_{n=0}^{\infty}(-1)^n(2n+1)a_n^* \tag{3}$$

$$g(0) = \frac{1}{iK_1}\sum_{n=0}^{\infty}(-i)^n b_n^* \qquad g(\pi) = \frac{1}{iK_1}\sum_{n=0}^{\infty}(i)^n b_n^* \tag{4}$$

the above equations can be solved by the continuity conditions based on 1.

2.2. Dynamic Generalised Self-Consistent Model

The DGSCM proposes a three-phase media: an inclusion of radius a surrounded by a spherical shield of radius b immersed in a fluid-matrix. The equations of continuity in the both interfaces: inclusion-shield and shield-effective medium, are written as two-phase system Yang (2003), and the longitudinal and shear wavenumbers are computed by iterative processes:

$$k_{p+1}^2 = k_p^2 - 4i\frac{c}{\pi a^2}f(0) - \frac{4}{k_p^2}(\frac{c}{\pi a^2}^2(f^2(0) - f^2(\pi)))$$
$$K_{p+1}^2 = K_p^2 - 4i\frac{c}{\pi a^2}g(0) - \frac{4}{K_p^2}(\frac{c}{\pi a^2}^2(g^2(0) - g^2(\pi))) \tag{5}$$

where the volume fraction c is expressed as a^3/b^3, the initial value k_0 is given by the WT k_m, and K_0 values is

$$K = 2\pi f\sqrt{\frac{\rho}{\mu}} \tag{6}$$

$$\rho = (1-c)\rho_m + c\rho_i \tag{7}$$

$$\mu = \mu_m(1 + c\frac{4(\mu_i - \mu_m)(1-\nu_m)}{(3-4\nu_m)\mu_i + \mu_m}) \tag{8}$$

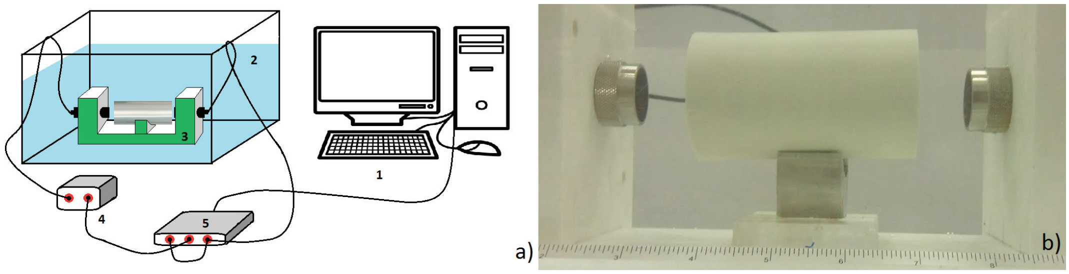

Fig. 1. a)Experimental setup b)Position of the specimen with the transducers.

and ρ_*, μ_* and ν_* are the density, shear modulus and Poisson ratio of medium * (indexes *m* stands for matrix and *i* for the inclusion), respectively.

3. Experimental Methodology

In order to analyze the frequency-dependence of the phase velocity and attenuation of an ultrasonic pulse, traveling throughout a cement-paste specimens with different w/c ratio, and compared to the predicted theoretical values, a through transmission ultrasound setup is proposed. The specimens had been manufactured followed the ASTM standard, and the experimental assembly has been in developed under far field considerations.

3.1. Cement-paste probes

White Portland cement (CPC-30R-B) was used to prepare the cement paste specimens with w/c ratio of 0.4, 0.5 and 0.6 by weight in accordance with to the C305-99 (ASTM International (2013)) standard. The probes were cast into cylindrical molds of 5 cm in diameter and 10 cm height. They were placed in a room at constant temperature of 23 *C* about 28 days. For ultrasonic evaluation process, the specimens were vacuum saturated with distilled water at 20 mbar. It has shown that the water absorbed by the specimen can be related to the porosity of the probe via weight difference; at higher the w/c ratio the porosity of the media decreases.

3.2. Experimental Setup

Through-transmission ultrasound method was used to acquire the signals coming from the different cement-paste specimens. It consists of a HandyScope HS3 (Handy (2002)), a preamplifier, a PC to storage the data and two pairs of unfocused ultrasonic transducers of 500 KHz and 1 MHz of operating frequency (see Figure 1a). The HandyScope HS3 is a digital oscilloscope and function generator that allows the design of excitation pulses with different wave shapes and frequencies. For phase velocity and attenuation measurements of 18 cement-paste blocks the transducer were excited by a 12V modulated sine wave of short duration and the received data was acquired at a sampling rate of 50 MHz. The experimental assembly is shown in Figure 1b where the cement-paste specimens were located along the main axis of the transducers, assuring that the cylindrical bases were parallel to the transducers surface. The experimental phase velocity and attenuation are determined by

$$V_L = \frac{d}{\Delta t + \frac{d}{V_w}} \tag{9}$$

4. Results

The experimental data were collected from 18 cement-paste cylindrical blocks, arranged in sets of six specimen and each set were built at different w/c ratio (0.4, 0.5 and 0.6). For each experimental configuration transducer-probe, 500 signals were acquired and averaged.

The longitudinal experimental and theoretical phase velocities and attenuation for different w/c ratio specimens and 500 KHz transducer operating frequency are shown in Figure 2.

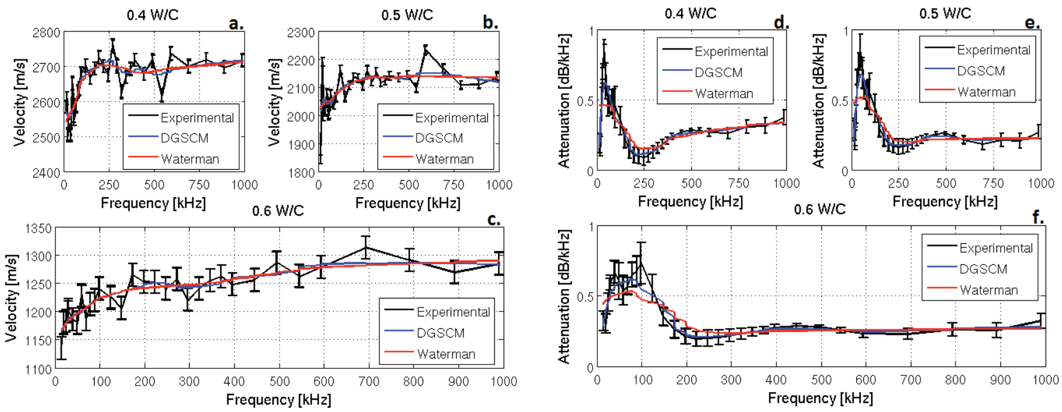

Fig. 2. Phase velocity and attenuation for different ratios W/C for a frequency of 500 kHZ.

The overall phase velocity decreases as the w/c ratio increases, where the phase velocity given by the 0.6 w/c ratio case is very close to V_w (see Figure 2a). On the other hand, the behaviour of the frequency-dependent attenuation, as plotted in Figure 2b, is that a higher the w/c ratio is the loss of energy is diminished. The phase velocity behaves quite similar when the specimens are radiated with a 1 MHz ultrasonic pulse, however the attenuation decreases rapidly respect to the first case of 500 KHz pulse as shown in Figure 3.

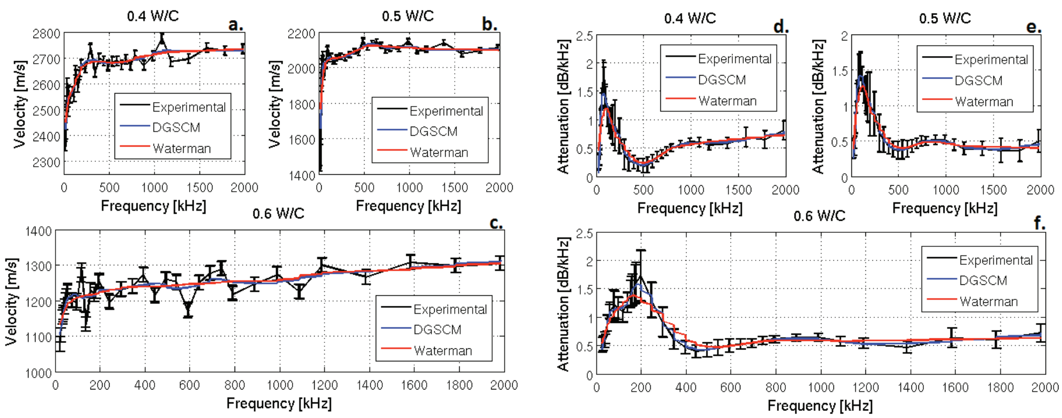

Fig. 3. Phase velocity and attenuation for different W/C ratio for a frequency of 1 MHZ.

5. Conclusions

In this article the results of theoretical and experimental cement-paste ultrasonic study are shown; transmission measurements were made in cement materials and they were compared with theoretical curves obtained by homogenization models. It was determined that for analyzing these materials is necessary to use narrow band pulses of different frequencies, that allows the measurement of frequency-dependent phase velocity and attenuation. The theoretical models relate the wavenumber with phase velocity and attenuation as a function of the scatterers concentration in the media with no interaction between them. On the other hand the experimental data relate the phase velocity and attenuation with the w/c ratio. The combined results can lead to characterize the cement-paste material. A further analysis must carried out for the shear phenomena.

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