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Characterization of ultrasonic properties of concrete

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ABSTRACT

The objective of this study is to verify the applicability of the dynamic effective medium theory to the analysis of wave propagation in a multiphase multiscale material such as the concrete. Ultrasonic measurements and numerical calculations of longitudinal wave speed and attenuation are performed for concrete specimens with different material contents. Comparisons between the numerical and experimental results show that the theoretical model captures some essential characteristics of ultrasonic waves in concrete. The effects of size, mechanical properties, and bonding condition at the interfaces of aggregates on the wave dispersion and attenuation are investigated.

1. Introduction

Ultrasonic methods have been widely used for the nondestructive evaluation of mechanical properties (Popovics et al., 1990; Jacobs and Owino, 2000; Yaman et al., 2002; Aggelis and Philippidis, 2004; Philippidis and Aggelis, 2005) and the monitoring of internal damage progression (Kim et al., 1991; Popovics and Popovics, 1992; Selleck et al., 1998; Punurai et al., 2006) in cement-based materials. One may expect to obtain speed and attenuation of longitudinal waves from an ultrasonic measurement on concrete. These ultrasonic parameters are influenced sensitively by the mechanical and rheological properties of constituents, microstructure, bonding quality at the interfaces between different constituents, and distributed microdamage. Therefore, properties, microstructure, and damage state of a concrete specimen can possibly be investigated with the measured ultrasonic wave speed and attenuation data. For a quantitative evaluation, one needs a theoretical model that relates these material parameters to the ultrasonic parameters. However, modeling of ultrasonic wave scattering and propagation in concrete is overwhelmingly intensive due to its complex structural and constitutional characteristics. There have been few theoretical investigations (Aggelis et al., 2005) into the modeling of ultrasonic wave propagation in concrete; ultrasonics studies on concrete have been purely experimental and thus evaluations based on the ultrasonic testing have often been qualitative and data-driven (Del Rio et al., 2004).

Numerous theoretical models have been proposed for elastic wave propagation in inhomogeneous materials. Most of the existing models are capable of analyzing wave propagation in two-phase composites in which one material acts as a matrix and the other one as an inclusion. The size and mechanical properties of inclusions are usually assumed to be identical. Moreover, these models assume an isolated microstructure, namely, every inclusion is completely isolated by the surrounding matrix, having no chance to be in contact with other inclusions. These assumptions are quite acceptable in most of the industrial composite materials. The microstructure of concrete is, however, by far more complex (Mehta and Monteiro, 1993). First, the aggregate size varies from a few hundred micro-meters to several centimeters. Second, aggregates with

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different mechanical properties are mixed together making the concrete product to be a multiphase material. Finally, the way that aggregates are distributed in concrete cannot always be assumed to be an isolated microstructure. Since the volume fraction of aggregates is usually higher than 50%, aggregates are densely packed; spaces between larger aggregates are efficiently filled by smaller aggregates in different sizes allowing contacts between the aggregates. These multiphase multiscale microstructural characteristics make it intractable to employ most of the existing models in predicting the wave propagation in concrete.

Unlike other models (Kim et al., 1994; Yang, 2003; Kim, 2004; Chaix et al., 2006), the dynamic effective medium theory (Kim et al., 1995) does not assume a specific microstructure, which allows us to effectively handle a randomly aggregated microstructure (Niklasson et al., 1981) which may be too complicated to describe with a geometrically well-defined representative volume element such as the three-phase model (Yang, 2003; Kim, 2004). Without assuming a specific microstructure, this theory was capable of predicting excellently the wave propagation characteristics of different composite materials in a wide range of volume fraction (Kim et al., 1995: Kim, 1996; Kim, 2003). In addition, the dynamic effective medium theory can readily be extended to multiphase multiscale materials, which is largely impossible with most of other models.

In this paper, we apply the theoretical model of Kim et al. (1995) to a multiphase multiscale material configuration as a model for concrete. The model is examined by comparing the theoretical results with ultrasonic measurement data. Discussions are given on the wave propagation characteristics in concrete and on the way to improve the present model by considering more realistic microstructural characteristics of actual concrete.

2. Wave propagation model – the dynamic effective medium theory (Kim et al., 1995)

The total wave field in an inhomogeneous medium can be decomposed into two parts: the mean field and the fluctuating field. The mean field is considered to be related with the effective medium that has the effective properties of the inhomogeneous medium (Fig. 1). Then, the fluctuating field is the wave field due to the random deviation of material properties from the effective (average) properties. Therefore, the effective properties may be determined by seeking a condition under which the spatial average of the fluctuation field vanishes. A simplest way to implement this idea is the self-consistent embedding. The true matrix and the inclusions are embedded in the effective medium having yet unknown elastic properties. Then, the properties of the effective medium are determined by setting the ensemble average of the total scattering field to be zero. Since the computation of the total scattering field is not feasible in general, the single scattering approximation is employed as shown in Fig. 1. Assuming that the mean field is a plane wave and expressing the self-consistency conditions in terms of the forward scattering amplitudes, the conditions for the effective properties of an N-phase composite material are obtained (Kim et al., 1995),

$$\sum_{i=1}^{N} v_i \delta\rho^i \int_{\Omega_i} \mathbf{u}^i \times \nabla \exp(-i\mathbf{k}_l^e \times \mathbf{r}) \mathrm{d}\Omega = 0 \tag{1}$$

$$\sum_{i=1}^{N} v_i \delta\lambda^i \int_{\Omega_i} \Delta^i \exp(-i\mathbf{k}_l^e \times \mathbf{r}) \mathrm{d}\Omega = 0 \tag{2}$$

$$\sum_{i=1}^{N} v_i \delta\mu^i \int_{\Omega_i} \mathbf{E}^i : \nabla\nabla \exp(-i\mathbf{k}_l^e \times \mathbf{r}) \mathrm{d}\Omega = 0 \tag{3}$$

where v_i is the volume fraction of i-th medium; $\delta\rho^i$, $\delta\lambda^i$, $\delta\mu^i$ are the deviations of the density, Lame constants of the i-th medium from those of effective medium; $\mathbf{u}^i$, Δ^i, $\mathbf{E}^i$ are the displacement vector, dilatation, strain tensor inside the i-th inclusion (Ω_i) produced by the scattering; $\mathbf{k}_l^e$ is the wave number of the mean field (a plane longitudinal wave). Note that for simplicity, the scatter model is taken to be an equivalent sphere as shown in Fig. 1b, so the ensemble average over the composition,

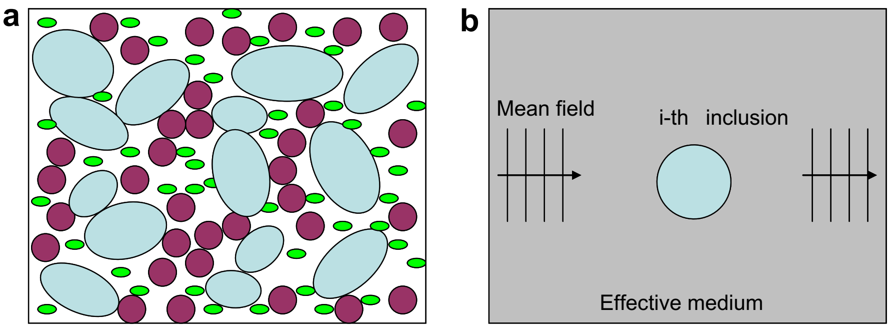

Fig. 1. Schematic of self-consistent embedding. (a) Model for a multiphase, multiscale material and (b) single scattering model embedded in the effective medium.