MICROMECHANICAL ASSESSMENT OF ULTRASOUND VELOCITY IN ENTRAINED AIR CEMENT PASTE

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Abstract

This article deals with the correlation between porosity and ultrasonic wave velocities of dry entrained air cement paste material. In order to vary the cement paste macroscopic porosity, an entrained air admixture was used within the studied samples. The water content was maintained constant by fixing the water/cement ratio to 0.4 in all samples. Based on the micromechanical modeling of a two-phase composite, the mechanical (bulk and shear moduli) and ultrasonic (longitudinal and transverse velocities) properties of the dry entrained air cement paste material were determined. Both longitudinal and transverse velocities were measured accurately using a setup specially designed for the study. First, the experimental and micromechanical obtained results showed that the correlation between acoustic and hydraulic parameters follow the expected trends. Longitudinal and transverse velocities decrease with macroporosity. Secondly, the dilute inclusion and the Mori-Tanaka models provided good estimations of the acoustic parameters of the air entrained cement paste, for low macroporosity under 10%. Finally, the self-consistent model succeeded in describing the dry air entrained acoustic parameters for all the considered macroporosity.

Keywords: cement paste, air-entrained, ultrasound, micromechanical models

1. Introduction

The follow-up of structure degradation is of great interest for many engineering fields [1]. In civil engineering, the degradation is generally caused by the penetration of aggressive agents through connected pores [2, 3]. Thus, porosity is one of the important parameters affecting the durability of cementitious material. It is considered as an indicator of durability [4].

The determination of pore fractions and their distribution represents a key issue for the quantification of the mechanical properties of cement-based materials. Aiming to achieve this purpose, non-destructive ultrasound on-site methods have been developed.

Elastic waves that propagate in porous material are directly related to its elastic parameters. In homogeneous, linear and elastic media, the compression and shear wave velocities, V_L (m/s) and V_T (m/s), are related to the material's elastic moduli by the well-known following expressions:

$$V_L = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} \quad ; \quad V_T = \sqrt{\frac{G}{\rho}} \qquad (1)$$

where K and G are the elastic bulk and shear moduli (MPa) and ρ is the density (kg/m^3).

As elastic moduli depend on porosity, this induces a relationship between porosity and ultrasonic velocity. Empirical expressions [5] and FEM numerical computations [6], that relate the porosity to the elastic moduli, were developed [7]. In this article, mechanical models based on micromechanical formulation, are investigated.

The micromechanical models make it possible to determine the overall properties of a composite material when the mechanical properties of all its constituents are known. Although they generally

give approximations of the unknown properties, these models are useful and have the advantage of providing physical information on the composite constituents.
The micromechanical modeling of cementitious materials still remains challenging. Few studies have dealt with cementitious materials [8], such as air-entrained cement paste. The latter is a composite material made up of micro-porous cement paste and macro-pores. In order to assess effective air-entrained cement paste elastic parameters, three micromechanical models were evaluated. These models were used to estimate the elastic shear and bulk moduli of air-entrained cement paste as well as the ultrasonic velocities.
In this article, the air-entrained cement paste samples subjected to both ultrasonic velocity and image processing porosity determination tests were described. Three models were selected among numerous micromechanical models present in the literature. Formulations of these micromechanical models were introduced: the dilute inclusion, Mori-Tanaka and self-consistent models. Finally, the micromechanical models evaluation were discussed.

2. Experimental Methods

The cement paste used in this experimental study was made up of cement CPA CEM I 52.5. The mixture was prepared with a fixed water to cement ratio W/C=0.4. In order to keep the water content constant and vary the porosity, different amounts of air-entrained (AE) adjuvant FOSROC Resi Air 200 were used: 0, 0.12, 0.25, 0.50, 1.5, 4.5, and 6% of the cement mass.
Broadband ultrasound spectroscopy [9, 10] was used to obtain ultrasonic parameters of the materials (longitudinal V_L and transverse V_T velocities).
Aiming to examine non-destructively and repeatedly the porous structure of the studied material, image-processing technique was investigated. It was used to quantify the volume fraction of the entrained air pores [11]. For more details on the above-mentioned experimental procedures, reader can refer to [9, 11, 12].

3. Micromechanical homogenization of the entrained air cement paste

3.1. Micromechanical material representation

In micromechanics, the expressions of the effective elastic properties are generally obtained from the relationship between the average stress and the average strain in a chosen representative volume element (RVE, [13, 14]).
The air-entrained cement paste material can be considered as a two-phase composite as illustrated in Fig. 1. One phase is the matrix: cement paste with no air-entrained admixture; the second is the inclusions, i.e. pores that are created by air-entrained adjuvant. The matrix was considered to be continuous with stiffness $\boldsymbol{C_0}$. Pores induced by the air-entrained were considered to be of spherical shape. Then, the inclusions were supposed to be spherical, arbitrary distributed in the matrix and of the same material with stiffness $\boldsymbol{C_1}$. The inclusions' volume fraction corresponds to air-entrained porosity (p). The matrix volume fraction is $(1-p)$. In the following subscripts, 0 and 1 respectively refer to the matrix and pores. $\boldsymbol{C}^{hom}$ refers to the homogenized stiffness tensor determined for the overall air-entrained cement past.

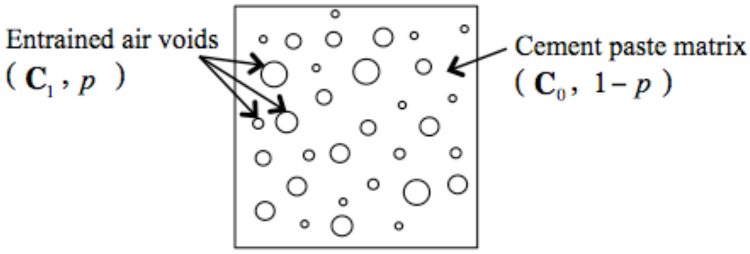

Figure 1 Schematic representation of air-entrained cement paste for micromechanical modelling

3.2. Micromechanical models description

Three micromechanical models were selected to predict the elastic properties of the cement paste with various air-entrained amounts. Each of these models is described below.

3.2.1. Dilute inclusion model

The dilute inclusion model is based on the Eshelby solution [15]. It makes it possible to calculate the strain inside an ellipsoidal inhomogeneity (of elastic tensor $\boldsymbol{C_1}$) embedded in an infinite matrix (of elastic tensor $\boldsymbol{C_0}$), when it is submitted to a far-field strain. The overall elastic-stiffness tensor of the composite is:

$$\boldsymbol{C}^{hom} = \boldsymbol{C_0} + p(\boldsymbol{C_1} - \boldsymbol{C_0})\left[\boldsymbol{I} + \mathbf{S}^{\boldsymbol{0}} : \left((\boldsymbol{C_0})^{-1}\boldsymbol{C_1} - \boldsymbol{I}\right)\right]^{-1} \quad (2)$$

where $\boldsymbol{C_1}$ and $\boldsymbol{C_0}$ are respectively the stiffness tensors of inclusions and matrix. $\mathbf{S}^{\boldsymbol{0}}$ is the Eshelby tensor [15, 16] depending only on the geometry of the inclusion and the Poisson ratio of the matrix. $\boldsymbol{I}$ is the fourth order identity tensor.

3.2.2. Mori-Tanaka model

The Mori and Tanaka model [17, 18] is based on the Eshelby single inclusion solution. It approaches the average strain in each inclusion by considering that each inclusion was subjected to the average matrix strain at infinity. Then, the overall elastic-stiffness tensor of the composite is:

$$\boldsymbol{C}^{hom} = \boldsymbol{C_0} + p(\boldsymbol{C_1} - \boldsymbol{C_0})\boldsymbol{T^{01}}\left[(1-p)\boldsymbol{I} + p\boldsymbol{T^{01}}\right]^{-1} \quad (3)$$

$\boldsymbol{T}^{\boldsymbol{01}}$ is the dilute strain-concentration tensor called also Wu-Eshelby tensor [19]. It is given by:

$$\boldsymbol{T^{01}} = \left[\boldsymbol{I} + \mathbf{S}^{\boldsymbol{0}} : \left((\boldsymbol{C_0})^{-1}\boldsymbol{C_1} - \boldsymbol{I}\right)\right]^{-1} \quad (4)$$

3.2.3. Self-consistent model

The self-consistent model is based on the Eshelby single inclusion solution. It was formulated by Hill [20] and supposed that each inclusion is surrounded by all the other phases and so by the average homogenized field. The model is then formulated using the Eshelby isolated inclusion solution, presented above, when assuming that the matrix has the composite properties. Then,

$$\boldsymbol{C}^{hom} = \boldsymbol{C_0} + p(\boldsymbol{C_1} - \boldsymbol{C_0})\left[\boldsymbol{I} + \mathbf{S}^{hom} : \left((\boldsymbol{C}^{hom})^{-1}\boldsymbol{C_1} - \boldsymbol{I}\right)\right]^{-1} \quad (5)$$

where $\mathbf{S}^{hom}$ is the Eshelby tensor depending on the geometry of the inclusion and the Poisson ratio of homogenized material. The homogeneous stiffness tensor can be determined by iteratively solving the previous expression.

4. Evaluation of micromechanical modeling of air-entrained cement paste

In order to evaluate the homogenized air-entrained cement paste properties using micromechanical models, elastic moduli of the cement paste with diminishing macropores' volume were needed. Thus, a reference cement paste sample with no air-entrained admixture was considered. Its mechanical properties were taken as the matrix properties of the air-entrained cement paste composites. These data were obtained from ultrasonic measurements on the reference sample using (Eq. 1). The values of bulk and shear moduli obtained for the cement paste at zero macroporosity are given in Table 1. The density ρ_0 was determined experimentally.

Table 1 Ultrasonic and mechanical properties of cement paste without air-entrained material.

	$V_L(m/s)$	$V_T(m/s)$	$K_0(MPa)$	$G_0(MPa)$	$\rho_0(kg/m^3)$
Reference Sample	3801.30	2310.94	12978	9456.3	1770.7

Fig. 2 & 3 shows the micromechanical and experimental evolution of normalized ultrasonic velocities with macroporosity for the dry air entrained cement paste. The longitudinal and transverse velocities were evaluated using the models presented above, based on two-phase formulations and assuming spherical inclusions. The same ultrasonic properties were directly measured on samples. Vertical error bars correspond to the standard deviation of velocity estimated from three measurements. Horizontal error bars refer to the standard deviation of macroporosity determined by image processing over 12 air-entrained cement paste sections.

The micromechanical and experimental velocities decrease when macroporosity increases. This trend is coherent with all the models described above, where bulk and shear moduli were assumed to be inversely proportional to the inclusion volume fraction.

According to Fig. 2 & 3, the dilute inclusion model overestimates both transverse and longitudinal velocities. This result was obtained for all macroporosities (all AE%) except for very low ones (less than 5%). Such trend was expected as this model assumes low inclusions fractions and no interaction between the inclusions. This explains the enlarging gap between the Eshelby estimates and the ultrasonic measurements as macroporosity increases.

The Mori-Tanaka estimates (Eq. 4) appear to fit better the experimental results but for macroporosity not exceeding 10%. Although the Mori-Tanaka model is considered to take into account the interactions between inclusions, its formulation is carried out while assuming that the matrix medium is a collection of non-interacting inhomogeneities. Thus, for a relatively high volume fraction (p > 10%), the model was not accurate in modelling the air-entrained cement paste composite nor in representing the experimentally found results.

In the self-consistent formulation (Eq. 6), each inclusion considers the matrix medium as the still unknown effective medium. In such a model, the interactions between the inclusions are considered in the matrix modelling. The latter argue the good agreement that is shown in Fig. 2 & 3 between the estimated self-consistent velocities and the ultrasonic measured ones.

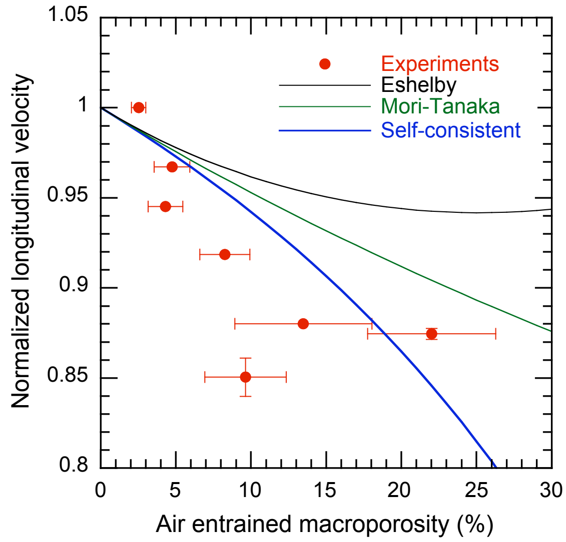

Figure 2 Experimental and estimated longitudinal velocity for dry cement paste material vs. macroporosity

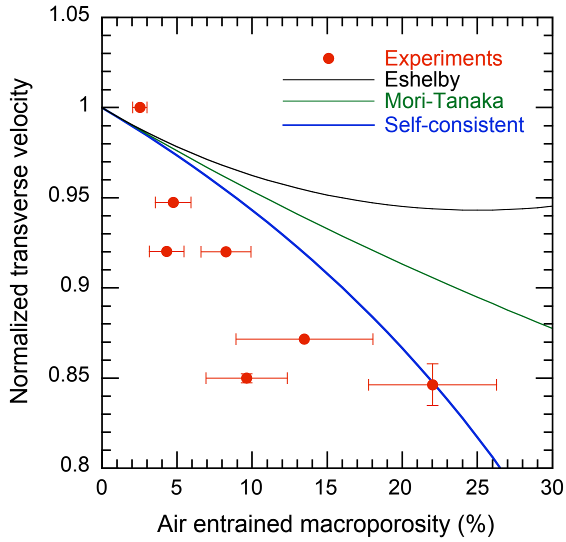

Figure 3 Experimental and estimated transverse velocity for dry cement paste material vs. macroporosity

5. Conclusion

The relationship between macroporosity and ultrasonic parameters of dry air-entrained cement paste was investigated in this study through micromechanical modelling. Selected micromechanical models reported in literature to predict mechanical properties (bulk and shear moduli) of two-phase materials were described. Air-entrained cement paste was considered as a two-phase material presenting a micro-porous cement matrix with arbitrary distributed macro-pores. The detailed micromechanical models were: the dilute inclusion, Mori-Tanaka and self-consistent models. The three models were suitable to model the air-entrained cement paste as a two-phase composite material.

The micromechanical predictions of the ultrasonic velocities of dry air-entrained cement paste were compared to experimental data. At low porosity, acceptable correlations were obtained between the macroporosity and acoustic velocities estimated by the Eshelby or Mori-Tanaka models. The self-consistent model gave a good representation of air-entrained cement paste, with changing macroporosity.

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