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Ultrasonic wave propagation in EPS lightweight concrete and effective elastic properties

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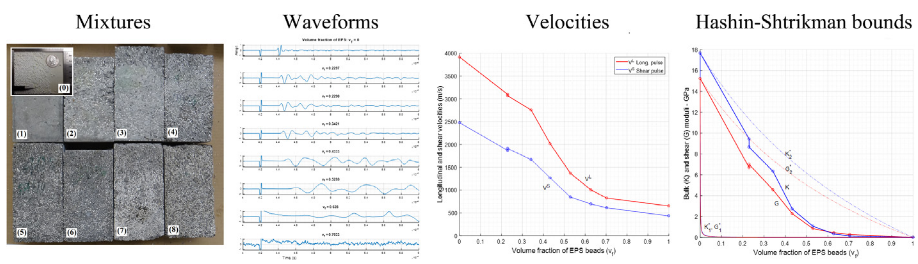
HIGHLIGHTS

- Ultrasonic longitudinal and shear waves are used to evaluate concrete with EPS beads.
- Volume fraction of EPS beads strongly influences waveforms and frequency spectra.
- Ultrasonic pulse velocity (UPV) decays as the volume fraction of EPS beads increases.
- Spectra of pulses shift to lower frequencies as the fraction of EPS beads increases.
- UPV-based elastic properties (K and G) fall within the Hashin-Shtrikman (HS) bounds.

GRAPHICAL ABSTRACT



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ABSTRACT

Although studies have been conducted to determine expanded polystyrene (EPS) concrete properties from mechanical experiments, nondestructive evaluation (NDE) is seldom applied to investigate this material. The present study uses ultrasound to evaluate lightweight EPS concrete. The first part of the study investigates EPS beads effect on ultrasonic pulse velocity and attenuation. It is demonstrated that the EPS beads strongly affect the waveforms, leading to a decrease in both longitudinal and shear pulse velocities, and shifting the frequency spectra to lower values. The second part of the research compares ultrasonically evaluated bulk and shear moduli of the mixtures with the Hashin-Shtrikman bounds.

1. Introduction

Frequently used to build canoes for the *concrete canoe* competitions between groups of Civil Engineering students in the United States, concrete mixtures with expanded polystyrene (EPS) beads have several other applications. In recent years, EPS lightweight concrete has been used more and more for both non-structural and structural applications, such as the construction of high rise buildings, floating platforms, and long-span concrete beams [1,2]. The term lightweight concrete usually refers to concretes that weight less than 1800 kg/m^3 [3] and the application of lightweight concrete in structural design has been introduced in building codes, e.g., ACI 318-14 [4].

Most of the research related to EPS concrete aims at determining properties of the mixtures with different volume fractions of EPS beads – such as compressive strength, modulus of elasticity, stress-strain behavior, tensile strength, durability, and permeabil-

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ity – through the application of direct mechanical experiments [1,2,5–8]. Saradhi Babu et al. [1,6] studied properties and performance of EPS concretes with fly ash and compared the results with a normal concrete without fly ash; the results indicated a linear relation between the increase in the volume ratio of EPS beads and the decrease in compressive strength. This linear inverse relation between EPS volume ratio and compressive strength, i.e., as the volume ratio increases the strength decreases, was also observed by Xu et al. [2]. Miled et al. compared the results from 3 lightweight concrete mixtures made with 1 mm, 2.5 mm and 6.3 mm EPS beads; the experiments showed that the variation of the modulus of elasticity as a function of the EPS volume fraction is the same for the three EPS beads sizes used, in addition, 110 mm × 220 mm cylindrical specimens are representative volume elements for 1 mm and 2.5 mm EPS beads concretes [7].

Nondestructive methods are seldom applied in the investigation of EPS concrete; the research published by Sri Ravindrarajah and Tuck, in 1994, is one of the first publications that addressed NDE of lightweight EPS concrete [8]. The authors used ultrasound to establish a correlation between ultrasonic pulse velocity and compressive strength; the same approach was applied later in the work by Saradhi Babu et al. [1]. This type of application of ultrasonic pulse velocity (UPV), though, i.e., the search for a correlation between longitudinal pulse velocity and compressive strength, follows the same approach traditionally used for conventional plain concrete since the pristine ages of ultrasonic testing of concrete [9,10].

An interesting aspect of EPS concrete analysis is the possibility of applying multiphase theories – such as Hashin-Shtrikman (HS) bounds [11] – to determine mixture elastic properties. Using ultrasonic longitudinal and shear pulse velocities and the mixture density, elastic properties can be readily calculated from classical linearized theory of elasticity [10,12]. The presence of inclusions (the EPS beads) in the concrete mixture, however, strongly affects the propagation characteristics of the ultrasonic pulses, leading, therefore, not only to the (expected) velocity variations due to elastic property changes, but also to changes in the waveforms and in the pulse frequencies [13–15]. Consequently, prior to the evaluation UPV-based elastic properties and their comparison with HS bounds, a careful analysis of the pulse waveforms has to be conducted. In the following, after describing the experimental program in detail, velocities and frequency contents analysis of the pulses used are discussed. The effective elastic properties are then evaluated using UPV and the HS bounds.

2. Experimental program

2.1. Materials, mixture design and samples preparation

As shown in Table 1, EPS concrete mixtures were prepared with increasing volume fractions of EPS beads: from 0.0% – Mix. 1: plain concrete mixture – to 70.33% – Mix. 8: mixture with the maximum amount of EPS beads. All mixtures were cast in steel molds from the same concrete batch, proportioned with Portland cement and siliceous aggregates. After mixing the plain concrete basic mixture with 0% of beads and casting the first specimen (Mix. 1), mixtures with increasing volume fractions were then obtained by successively adding EPS beads to the remaining of the mixture and continuously mixing the two materials – concrete and beads – during the entire process; at each step, EPS concrete specimens were cast. After casting all specimens, they were kept in ambient conditions and striped from molds after one day; they were kept in the fog room for 28 days and then tested with ultrasound. All specimens had a cross section of 88.62 × 88.62 mm and height of around 150 mm. Volume fractions v_f obtained, from plain concrete to maximum fraction of beads, were (Table 1): (1) 0.0000, (2) 0.2297, (3) 0.2298, (4) 0.3421, (5) 0.4333, (6) 0.5299, (7) 0.6280, and (8) 0.7033. Volume fractions for mixtures 2–8 were precisely calculated using each mixture density and the densities of the plain concrete mixture (2477.5 kg/m^3) and of the beads (12.0 kg/m^3). In Fig. 1, photographs of the EPS beads and mixtures are shown.

EPS beads diameters varied, approximately, from 1.0 to 2.0 mm; elastic properties of the beads used are listed in Table 1 as Mix. 9; longitudinal and shear ultrasonic pulse velocities, V^L = 625.80 m/s and V^S = 435.19 m/s, respectively, were calculated using EPS beads mechanical properties [16,17]. Mixtures 2 and 3 were designed with the same amount of EPS beads to work as a check in the experimental program; a very small variation the in the beads volume fraction (0.04%) and density (0.01%) between these two specimens cast occurred. Mixture 8, with v_f = 0.7033, and therefore a little more than 70% of its volume made of EPS, was the maximum volume fraction that could be obtained; beyond this volume fraction the fresh mixture was sandy, cohesionless.

2.2. Equipment, experimental setup, and testing procedures

Equipment used and experimental setup are depicted in Fig. 2. The main component was a commercial portable Pundit Lab pulse/receiver unit used to generate and receive the 500 V ultrasonic pulses; the unit was controlled by a laptop. In order to obtain accurate velocity and frequency measurements and also to improve signal-to-noise ratio an average of 128 waveforms, with 10^7 points each, was digitized and recorded with a sampling interval of $1.0 \cdot 10^{-9}$ s using an oscilloscope (Tektronix DPO2022B). Two pairs of broadband transducers with nominal frequency of 500 kHz (Panametrics models V101-RB – longitudinal – and V151-RB – shear wave) were used; each pair of transducers was firmly attached to opposite sides of the each specimen with couplants and pressed against the flat surfaces with c-clamps; the pulses propagated through the 88.62 mm distance between the parallel surfaces. Since *amplitude* measurements strongly depend on couplant film thickness and pressure applied on the transducers against the specimen surfaces – and these parameters could not be precisely controlled every time the transducers pairs are attached to the specimens – the recorded waveforms were analyzed with regard to velocity and frequency only.

3. Velocity measurements

Different approaches have been applied to measure UPV in pulse-through experiments to investigate materials. When the waveforms do not change considerably during the experiments, the transit time of the pulse propagating through the material can be measured using some amplitude threshold [13], the leading edge of the waveform [14], or the zero-crossing time position between amplitudes of opposite signs [18,19]. However, if the waveforms show relevant changes in their aspect during the experiment, energy-based approaches to evaluate group velocity of the pulses are more appropriate [13,15].

Table 1
Properties of mixtures used: volume fraction v_f of EPS beads, density ρ, ultrasonic longitudinal (V^L) and shear (V^L) pulse velocities, and mechanical properties: bulk (K) and shear (G) moduli. The first row, Mix. 1, is the plain concrete mixture used, with no EPS beads, and the last row, Mix. 9, lists EPS beads properties.

Mix.	Volume fract. v_f	Density ρ (kg/m^3)	V^L (m/s)	V^S (m/s)	K (GPa)	G (GPa)
1[a]	0.0000	2477.5	3913.51	2477.85	17.66	15.21
2	0.2297	1911.3	3097.87	1870.01	9.43	6.68
3	0.2298	1911.1	3066.95	1913.18	8.65	7.00
4	0.3421	1634.0	2755.85	1670.03	6.33	4.56
5	0.4333	1409.3	2015.57	1266.59	2.71	2.26
6	0.5299	1171.1	1367.10	846.24	1.07	0.84
7	0.6280	929.2	1003.50	696.49	0.33	0.45
8	0.7033	743.6	825.65	612.07	0.14	0.28
9[b]	1.0000	12.0	625.80	435.19	0.0021	0.0023

[a] Plain concrete mixture proportions (fraction in weight: cement, coarse aggregate, fine aggregate): 1.0:1.894:1.186; w/c: 0.265. Aggregate sieve distribution (mm, fraction in weight per 1.0 kg of cement): 12.5–9.5: 0.568; 9.5–4.7: 1.326; 4.7–2.3: 0.242; 2.3–1.1: 0.363; 1.1–0.6: 0.303; 0.6–0.3: 0.182; 0.3–0.1: 0.097.
[b] EPS pulse velocities were calculated from mechanical properties and density [16,17].