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Elastic properties of green expanded perlite particle compacts

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ABSTRACT

This paper describes an experimental and analytical study characterizing the elastic properties of packed beds of expanded perlite. Elastic moduli of packed beds of expanded perlite particles (expanded siliceous volcanic glass) were investigated by elastic wave velocity measurement along the axial direction. By adopting an isotropic model for the medium, the elastic moduli Poisson's ratio and Young's modulus were measured. Young's modulus increased nonlinearly with increasing bulk density. Poisson's ratio did not show a large variation with density and which may be understood in terms of the fabric of the medium (double porosity structure of the packed beds). During compaction to achieve different densities, some crushing of particles into smaller particles and platy debris occurred. Analyses were based on both the raw compaction densities and densities modified by removal of debris from consideration on the assumption that it is non-structural. Four analytical models were applied to predict elastic moduli of packed beds of expanded perlite particles within the porosity range 84-95%. Models were assessed on their ability to successfully predict elastic moduli of these highly porous bodies for both cases: using the raw compact density and the modified density. It was found that the Wang (Minimum Solid Area) model was able to estimate Young's modulus and the Gibson and Ashby model was reasonable for the average behaviour of both elastic moduli. The best agreement was found for the Phani model with our modified shape factor.

1. Introduction

Perlite is a glassy volcanic rock of silicic or rhyolithic composition typically formed by the hydration of obsidian. Upon rapid controlled heating within the softening temperature range 760–1100 °C, the combined water in perlite grains is converted to pressurized steam that causes expansion of perlite to 4–20 times its original volume. The expanded form of perlite (EP particles) has low density, high porosity and offers excellent thermal and acoustic insulating properties, chemical inertness, physical resilience, fire resistance, and water retention properties [1]. In a previous study [2], a novel lightweight foam core composite was developed by embedding a high volume fraction of EP particles in a matrix of epoxy resin, and subsequently compacting the mixture to different target densities. Containing a high volume fraction of EP particles, EP/epoxy foams had the structure of a packed bed of EP particles with epoxy resin filling the interstices. Compression tests were conducted on the EP/epoxy foams and their compressive properties were found to be independent of particle size but highly affected by foam density. Attempts were made to measure and predict the elastic modulus of packed beds of EP particles and their contribution to the resulting EP/epoxy foam's elastic modulus. However, due to the limitations and inappropriateness of conventional quasi-static testing methods (e.g., compression tests) for powdered materials [3–6], the accuracy of the measured Young's modulus was questionable. Using Voigt and Reuss models, an upper and a lower bound were estimated for the Young's modulus of EP particles in EP/epoxy foams. It was found that EP particles show Reuss-like behaviour similar to metals but atypical of non-plastic materials.

In this study, the elastic properties of packed beds of EP particles were characterized by means of elastic wave propagation (compression and shear) along the axial (compaction) direction for a wide range of compaction densities. By adopting an isotropic model, the Young's modulus and Poisson's ratio are used to characterise the elastic response of the medium. In addition, five analytical models were used to study the elastic moduli-porosity relations and to predict the elastic moduli of the EP particles measured experimentally. This approach is opposite to what has been frequently adopted in metallurgy where the properties of sintered products are estimated from those of the powder. It will help to estimate the properties of EP/epoxy foams having different volume fractions of EP particles in order to produce foams with different porosities.

2. Experimental procedure

2.1. Material

EP particles, supplied by Industrial Processors Limited (INPRO), were sieved in the size range 2-2.8 mm. The chemical composition provided

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by the supplier is presented in Table 1. Fig. 1 shows two SEM images taken from (a) the outer surface and (b) the mid-cross section of an expanded perlite particle. It can be seen that the outer surface is covered with both closed and open pores and has a froth-like structure. Fig. 1b reveals that internally the expanded perlite has a structure mainly composed of closed cells sealed off from their neighbours by membranous walls [7] which are almost uniform in size.

Tapped density of the perlite particles was measured using a tapping device with a graduated measuring cylinder of 100 ml. After every 20 taps, the cylinder was rotated to minimize any possible separation of the mass during tapping down. Five hundred taps were conducted for each density measurement and the average of five measurements was found to be 0.086 g/cm^3 (Standard deviation: 0.0033 g/cm^3). Particle density was also measured via the wax- immersion method (ASTM C914-95) and found to be 0.183 g/cm^3 (Standard deviation: 0.010 g/cm^3).

2.2. Sample preparation

A cylindrical compaction mould made of Al was used to produce samples of packed EP particles 45 mm ± 0.015 in height and 80 mm in diameter. Perlite particles were introduced into the mould assisted by an Al sleeve of the same diameter to avoid spillage. The target compaction densities were achieved by controlling the mass of EP particles within a constant volume. To ensure homogeneity and minimize variations in density, specimens were compacted in several layers (up to five). The compaction process was carried out in a 50 kN computer-controlled load frame using a constant displacement rate of 1.0 mm/min. Lubricant oil was used to minimize friction between the piston and the walls of the mould. Fig. 2 illustrates the compaction stress as a function of density of the EP particle bed.

Solid perlite was prepared by grinding 27 g of perlite particles with a mortar and pestle and sieving to <250 μm. The powder was transferred into a mould and uniaxially pressed into pellets at 146 MPa. The pellets, resting on a bed of alumina powder, were heated at 10 °C/min to the sintering temperature of 1100 °C and held for 12 h. Subsequently the samples were cooled at 10 °C/min to 450 °C and held for an hour before cooling at the same rate to 300 °C when the furnace was turned off and the samples left to cool slowly. Sintered pellets were cut and polished into samples of 30 mm in diameter and 16 mm high. Densities of the prepared sintered pellets were measured at room temperature using the Archimedes method from which the value of 2.3 g/cm^3 (standard deviation 0.05 g/cm^3) was found.

2.3. Determination of dynamic moduli

Elastic stress waves propagate in materials by inducing infinitesimal elastic deformation. Hence, wave propagation equations which are based on elasticity theory can be used to measure elastic moduli of a material, if elastic wave velocities and densities are measured independently [9,10]. Two wave types propagate in extended elastic solids: (i) compression waves in which particle displacements are in the direction of the wave propagation, and (ii) shear waves in which particle displacements are perpendicular to the direction of the wave propagation. In an isotropic linear elastic body, in which the propagating wave does not interact with the boundary of the medium, compression (or P-wave) (C_P) and shear (C_S) wave velocities are given by:

$$C_S = \sqrt{\frac{\mu}{\rho}} \tag{1}$$

$$C_P = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{\lambda + 2\mu}{\rho}} \tag{2}$$

Table 1
Chemical composition of expanded perlite [8].

Constituent	Percentage present
Silica	74.0%
Aluminium Oxide	14.0%
Ferric Oxide	1.0%
Calcium Oxide	1.3%
Magnesium Oxide	0.3%
Sodium Oxide	3.0%
Potassium Oxide	4.0%
Titanium Oxide	0.1%
Heavy Metals	Trace
Sulphate	Trace

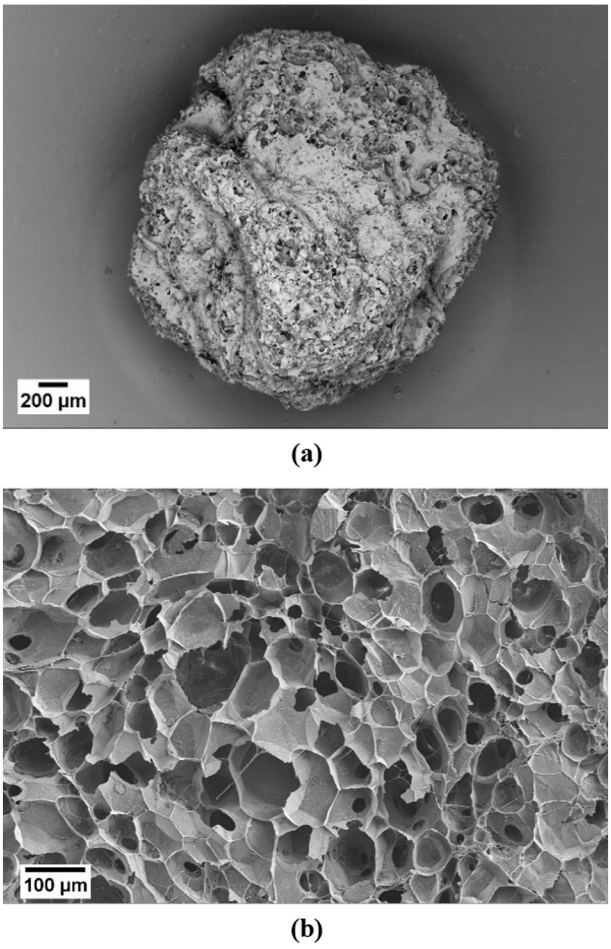

Fig. 1. SEM images showing (a) external structure of a perlite particle; (b) the internal structure of a perlite particle.

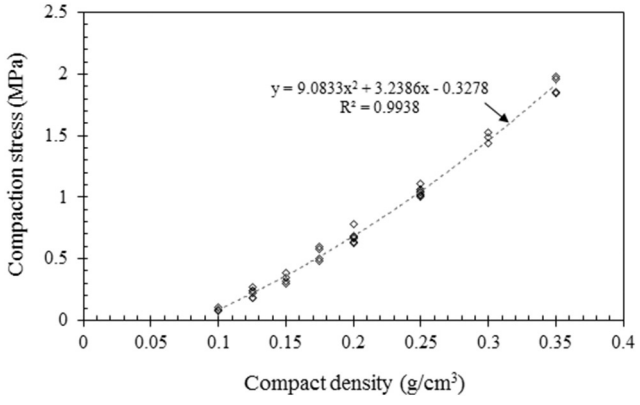

Fig. 2. Compaction stress versus the density of the packed bed of EP particles.