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Note

The relation between particle density and static elastic moduli of lightweight expanded clay aggregates

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ABSTRACT

Lightweight expanded clay aggregates are one type of artificial lightweight aggregates (LWAs) which have widespread application. They are produced in a rotary kiln. Output aggregates of kiln often contain a wide grading curve. The micromechanics method with some simplifications has been used for determining the elastic modulus of the different sizes of these aggregates. In general, the smaller the LWA particle size, the higher is the density. The effect of the density and size of aggregates on elastic moduli are investigated in this research. Two groups of quaternary lightweight expanded clay aggregates are used, with each group produced under the following identical conditions: particle density within the range of 480 to 1100 kg/m^3 and the domain sizes from 4 to 14 mm. The elastic modulus of expanded clay aggregates were determined by the micromechanics method and using the Mori–Tanaka model based on the elastic properties of mortar matrix and lightweight concrete which were determined experimentally. Based on results the elastic modulus of aggregates ranged from 0.6 to 6.3 GPa and there is a linear relation between the elastic modulus and the particle density of lightweight expanded clay aggregates. Their elastic modulus exponentially decreases with the increase in particle size.

1. Introduction

Aggregates of mineral origin having a particle density not exceeding 2000 kg/m^3 or a loose bulk density not exceeding 1200 kg/m^3 are named lightweight aggregates (LWAs) (EN13055-1, 2002). They are usually made from natural raw materials like clay, slate, shale, etc., and from industrial by-products like fly ash, slag ashes, etc.

LWAs can be used in a wide range of applications, such as: thermal and acoustic insulation, manufacturing of precast structural units and structural lightweight concrete, geotechnical applications, gardening and hydroponics (Bartolini et al., 2010; Bodycomb and Stokowski, 2000; Mason, 2000; Weinecke and Faulkner, 2002). The assigned application depends on all their physical, chemical and mechanical properties. So due to the application of LWAs in various industries, the property of these aggregates is important.

Lightweight expanded clay aggregates are manufactured in over 20 countries with various brand names such as "Laterlite" in Italy, "Liapour" in Spain, "Argex" in France, "Keramzit" in Russia and "Aglite" in South Africa. Furthermore, they are produced in Denmark, Finland, Norway, Portugal, Germany, Italy and Iran with the "Leca" (Lightweight Expanded Clay Aggregate) trade mark (http://Lecaworld.com/whatis.html).

They are produced in a horizontal rotary kiln at about 1200 °C by a wet process, using bloating clay. They are made by mixing clay and water into a paste. The paste is fed into the higher end of the rotary kiln where it is broken into smaller granules by chains. Thus, they form aggregates of random sizes and a rounded shape while passing through the rotary kiln where they are sintered to a glassy material (Chandra and Berntsson, 2002).

Particle density usually decreases by increasing output grain diameter. Furthermore, aggregates with different densities can be produced by changing the production process. They are classified according to size or loose bulk density. For example, Leca4–10 means lightweight expanded clay aggregates with grain diameters ranging from 4 to 10 mm; Leca700 means Leca with a bulk density of 700 kg/m^3 (European Union-Brite EuRam III, 2000; Mazaheripour et al., 2011).

Take note that for the non-uniform grading curve, this classification is not accurate, since the denser the Leca, the more is its strength; a heavier Leca is called "structural Leca" and it has more applications for use in high-strength concrete. For example, common Leca is used in Mazaheripour et al. (2011) and structural Leca is used in Costa et al. (2012). The literature on Leca related to its mechanism of formation and engineering aspects for use in concrete, etc. is extensive (for example at Al-Bahar and Bogahawatta, 2006; Bogas et al., 2012; Kvande, 2001), but literature about their mechanical properties is limited. The purpose of this study is to determine the relation between the particle density and the elastic moduli of Leca. Also the modulus difference between grain sizes on a kiln process is investigated.

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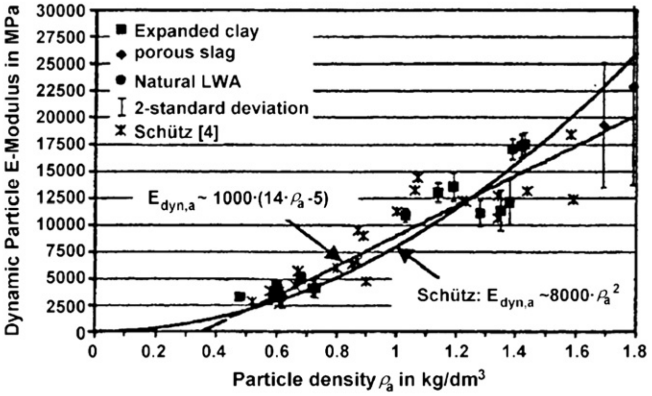

Fig. 1. Dynamic E-modulus of different lightweight aggregates and its dependence on the particle density (Chandra and Berntsson, 2002).

So in order to determine the density effect on the elastic moduli of the aggregates, elastic moduli of eight types (two groups of quaternary aggregates) of Leca, produced by an Iranian Leca factory, are determined by a combination experimental and theoretical approach.

2. Elastic modulus of LWAs

In general, the elastic modulus is the ratio of normal stress to the corresponding strain under a compressive load that is below the proportional limit of the material. However, due to the small dimensions and anisotropy of LWA particles, the elastic modulus of LWAs cannot be determined by a direct test and therefore, the standard test method is not applicable.

Because range dynamic and static elastic moduli of concrete are similar in terms of quantity, some researchers have used the dynamic elastic modulus to serve as the static elastic modulus (FIP, 1983). The main reason for this is that the dynamic elastic modulus of an aggregate can be calculated by ultrasonic measurement. A parabolic and linear relation between the dynamic elastic modulus and the particle density is shown in Fig. 1. But, the ultrasonic test is not suitable because of sample preparation and its procedure, which is performed on a single aggregate (Nilsen et al., 1995).

Nilsen et al. (1995) presented a method that is based on composite materials theory to estimate the elastic modulus of LWAs, and obtained the elastic moduli of three different expanded shale types of LWAs, using the Mori–Tanaka model. Yang (1997) used micromechanical methods to estimate the static elastic modulus of LWAs which were made of cement and fly ash. Nilsen et al. (1995) and Yang (1997) supposed the Poisson ratio of aggregates in the formulation of their research.

Chen et al. (2003) proposed a constituent model that is based on the actual distribution of coarse LWAs in hardened concrete to estimate the elastic modulus of LWAs in hardened concrete. They assumed that a spherical coarse aggregate is positioned at the center of a concrete cylinder, and an equation was proposed based on the modulus of mortar and concrete, and volume fraction of the aggregate by finite-element modeling.

However, the elastic modulus of an aggregate can depend on the density, the material which the aggregate is composed of and its pore structure, or the shape and volume of the pores in the aggregate and the irregularity of its texture (Zhi, 2007).

In this research by the combination of each type of aggregates with cement–sand mortar, and by building cylindrical samples of two-phase composite materials, the elastic properties of matrix and composite samples are determined. Then, using experimental results and relations obtained from the Mori–Tanaka model, the elastic moduli of aggregates are determined.

Lo and Cui (2004) demonstrate that the "Wall Effect" does not exist on the surface of expanded clay aggregates in lightweight concrete by SEM and BSEI imaging, resulting in a better bond and much thinner interfacial zone than the normal concrete. So, materials which are produced by Leca and cement–sand mortar can be considered a two-phase composite material. Considering the nature of Leca, their shape is assumed as a complete sphere in this research.

3. Theoretical background

The micromechanics of composite materials are aimed at determining the macroscopic (or effective) composite properties through models which incorporate the microstructural details. One method is homogenization techniques. They are applied to finding the appropriate homogenized (or averaged) equations which describe the mechanical deformation of a representative volume element (RVE) of the composite. Averaging theorems, which normally consider a random and homogeneous inclusion distribution, provide the volume-averaged stress and strain fields in each phase (Nemat-Nasser and Hori, 1999).

Generally, in order to demonstrate the homogenized effective macroscopic response of such materials, the relation between averages turns to be

$$\langle \sigma \rangle_\Omega = C^{\text{eff}} \langle \varepsilon \rangle_\Omega \tag{1}$$

where

$$\langle \alpha \rangle_\Omega = \frac{1}{|\Omega|} \int_\Omega \alpha \ d\Omega \tag{2}$$

and where $\langle \sigma \rangle_\Omega$ and $\langle \varepsilon \rangle_\Omega$ are the volume average stress and strain tensor fields within a statistically representative volume element (RVE) of volume $|\Omega|$ and "α" can be replaced by stress (σ) or strain (ε). The quantity C^{eff}, is known as the effective elasticity tensor.

Table 1
Leca groups and their properties.

Leca type	Group name	Size range (mm)	Mean size (mm)	Particle dry density (kg/m³)	Loose bulk density (kg/m³)	24 h water absorption (%)	Crushing resistance (N/mm²)
Common	C1	3.36–4.76	4.1	695	406	21.6	1.74
	C2	6.35–8.0	7.2	580	323	22.3	1.17
	C3	8.0–11.2	9.6	503	279	24.1	0.87
	C4	12.7–16.0	14.3	481	257	26.2	0.82
Structural	S1	3.36–4.76	4.1	1106	592	12.7	3.62
	S2	6.35–8.0	7.2	871	484	12.2	3.01
	S3	8.0–11.2	9.6	828	462	13.5	2.11
	S4	12.7–16.0	14.3	806	432	13.0	2.15