International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-11, September 2019

Micro-Mechanical Properties of Expanded Clay Particles

Haithem Ben Jamaa, Latifa Elgezal, Mehrez Jamei

Abstract**: *The aim of this paper is to study the micro-mechanical behavior of an industrial crushable and highly porous granular material. Lightweight Expanded Clay Aggregates (LECA) was selected in this research for testing thanks to its brittle nature and highly porous character which makes it easier to study the crushable behavior of this material. LECA's micro-mechanical properties were identified to understand the parameters that affect particle's crushing. Uniaxial compression tests, consisting on compressing the particles between two rigid platens, were made on a set of single LECA's particles to investigate the force displacement response and the Hertzian behavior was identified as the contact law. The particles' strengths were determined for tested granules using the crushing force and grains' Young moduli were calculated using the suggested contact law. Due to their high variability, the particles' crushing stress and their Young moduli were related to particle's dimension using a suggested power law to predict these mico-mechanical properties. Results have shown a high dependency between the particle's micro-mechanical properties and their dimensions.***

Index Terms**: *Expanded clay, particle crushing, uniaxial compression test, micro-mechanical properties.***

I. INTRODUCTION

Lightweight aggregates (LWA) are increasingly employed in many civil engineering applications. They are used in road construction, tunneling, structural backfilling around foundations, retaining walls, and bridges' abutments. Usually chosen in order to reduce the applied load transmitted to the foundation's soft clayey soil [1–6]. The significant internal porosity of such aggregates explains their low density (about 40% that of natural aggregate), thermal and acoustic insulation, and high resistance to fire and chemical attacks [7]. Among lightweight materials, one could mention lightweight concrete, expanded perlite, and lightweight expanded clay aggregates (LECA). LECA is selected for this study since it is more and more used in civil engineering applications.

Expanded clay particles are obtained by introducing raw material inside a long rotary kiln while increasing temperature [1]. With this process, the newly formed grain is composed of a hard shell on the outer surface; while inside, the grain is filled with light and highly durable aggregate with a porous clinker-like structure [7]. This makes these aggregates known as double-porosity granular materials; which according to Ciantia et al. [8] are those aggregates in which two distinct scales of pore size could be identified (an inter-particle porosity and an intra-particle porosity). The inter-granular voids are those existing between particles among a assembly of granules, while the intra-granular ones are voids existing within individual grains[8]. In the case of expanded clay, the intra-granular porosity is composed of a set of voids which are randomly distributed inside the grain. The sum of the volume of these closed voids divided by the particle's total volume gives the intra-granular porosity.

It is in the early twenties of the last century that Stephen Hayde patented the process of fabrication of expanded clay granules [9]. Expanded clays are artificial clays that expand up to 5–6 times as a result of gas release when they are exposed to high temperatures (up to 1200 °C). LECA have bulk densities not exceeding 1 g/cm^3 and their particles' densities remain below 1.2 g/cm3. The porous nature of LWA is the principal cause of their relatively low crushing strength as compared to natural soils and rocks. Therefore, this work focused on relating particles characteristics to their crushing development. For this purpose, an experimental program was carried out on a wide sample of expanded clay granules to investigate how the particle's size could affect its mechanical behavior, especially crushing strength and Young moduli. Experimental results showed that particle's mechanical characteristics are randomly distributed within a same size range which is quite relevant to the random particle's internal porosity distribution. A power law suggested by Casini et al. [1] is then introduced to correlate the particle's mico-mechanical characteristics to its size. The correlation's results for both, the crushing stress and particle's Young moduli are satisfactory with a correlation factor near to 0.6.

II. EXPANDED CLAY PROPERTIES

Expanded clay particles used in this study are commercially sold under the name lightweight expanded clay aggregate (LECA). Three different classes of LECA are available depending on the grain size distribution (GSD). LECA S (S for small) refer to particles ranging in size from 1 to 5 mm, LECA M (M for medium) refer to particles ranging in size from 4 to 12.5 mm, and LECA L (L for large) refer to particles ranging in size from 10 to 20 mm. Fig. 1 shows samples from the different used LECA classes.

Manuscript published on 30 September 2019.
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Fig. 1 Expanded clay aggregates: LECA S, LECA M and LECA L (from left to right)

Scanning electron microscope (SEM) images were taken in order to visualize the double-porosity in expanded clay particles as shown in Fig. 3. These image show that the external shell of LECA particles is relatively more porous as the particle size decreases. The intra-granular void network looks to be randomly distributed inside the grain. In addition, internal porosity of LECA seems to be higher for larger particles, which can be related to the fabrication process

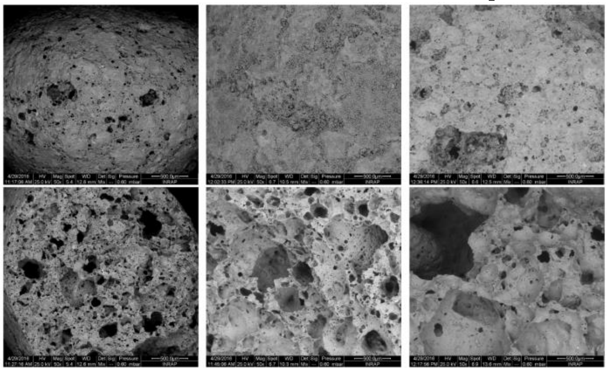

Fig. 2 SEM images of LECA, visualization of the internal porosity distribution

In order to understand the effect of grain size on crushing occurrence, 288 individual expanded clay particles were tested in this study. Seven different size intervals were selected as shown by Table 1.

Tab1 Selected size intervals for the tested LECA particles.

size interval (mm)	Number of tested particles
2-4	37
4-6	39
6-8	43
8-10	42
10-12	42
12-14	42
14-17	43

The mass of each tested particle (m_p) was determined using a scale with a precision of 10^{-3} g, while the volume (V_p) was obtained using a method similar to that of the French standard [10] by measuring the mass of mercury upfill due to particle. This volume measuring technique was used in order to maintain the grain's original properties. The particle's density (ρ_p) is then determined by dividing the grain's mass by its volume as described in Eqn 1.

$$\rho_p = \frac{m_p}{V_p} \qquad (1)$$

The scatter plot of density for all tested LECA particles is shown in Fig. 3. It is noticeable that densities have shown a random variation ranging from about 0.27g/cm^3 to 0.95 g/cm^3. This important variability is related to the industrial production process which includes heating of the raw material inside a rotary kiln. During this process the heat cannot be equally distributed for all particles which causes the expansion of the LECA particles with different internal porosities and therefore different densities. Table 2 shows the average densities and the standard deviations for all the studied LECA size intervals.

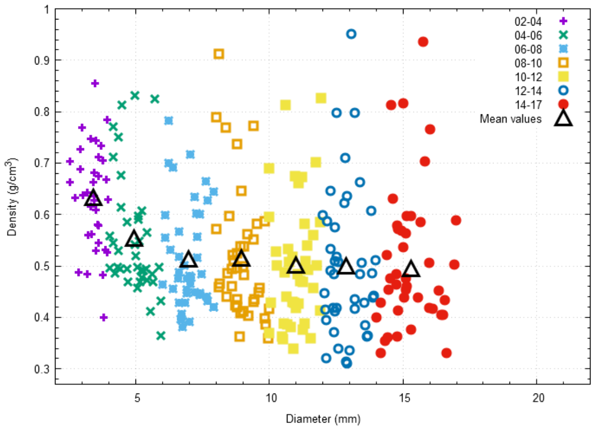

Fig. 3 Density scatter plot for all tested LECA

Table 2 Average values and standard deviations for measured densities of LECA particles

size interval (mm)	Average density (g/cm^3)	Standard deviation (g/cm^3)
2-4	0.633	0.095
4-6	0.555	0.114
6-8	0.513	0.099
8-10	0.514	0.124
10-12	0.501	0.120
12-14	0.499	0.140
14-17	0.494	0.123

It could be stated that the average density decreases with an increase in particle size. Meanwhile, the standard deviation is higher for larger particles, which can be also related to the production process in which bigger particles are more likely to have random defects during expansion.

III. Uniaxial Compression Test on a Single Grain

Uniaxial compression tests on single particles of LECA were performed on 288 granules. These tests have been used to characterize particle's strength and mechanical behavior. In this test, each particle is compressed between two parallel platens and under a constant rate of 2 mm/min. As shown by Fig. 4, the experimental setup is composed of a screw-driven load frame with adjustable loading speeds between 10μm/min and 10mm/min. Forces during the test were measured using a 1000 N load cell, while a 10-mm-range linear variable displacement transducer (LVDT) was used to measure displacement.

Retrieval Number: K15010981119/19©BEIESP
DOI: 10.35940/ijitee.K1501.0981119
Journal Website: www.ijitee.org

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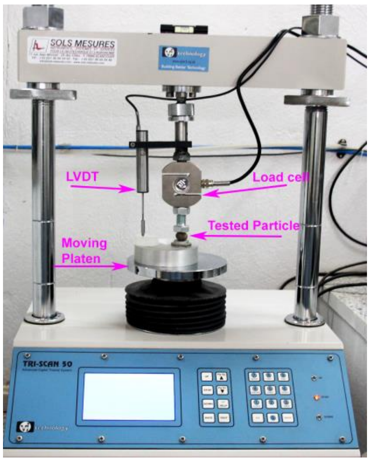

Fig. 4 Indirect tensile test on single grain

At the end of each test, the crushing force (F_c) is determined. Crushing is defined when the load drops suddenly or when the grain splits in several particles.

The breakage stress (σ_c) is then calculated using Eqn 2 in which Req represents half of the distance between the platens and was measured using digital caliper with a precision of 10 µm.

$$\sigma_c = \frac{F_c}{\pi R_{eq}^2} \quad (2)$$

Basing on the experimental results, the Hertzian contact model was considered as a more convenient model. From this the Young moduli were determined. This model, presented by Eqn 3, relates the applied force (F) to the grain's diameter (d), Young moduli (E), Poisson's ratio (v_p) and the applied displacement (u). Poisson's ratio was assumed to be constant and equal to 0.3. The data recorded before reaching a 2% strain, limiting value for the elastic behavior of LECA [6], was used along with the least squares method for determining the value of E.

$$F = \frac{1}{3}\left(\frac{E}{1-\vartheta_p^2}\right)\sqrt{du^3} \quad (3)$$

Fig. 5 shows examples of the fitting results for some tested particles.

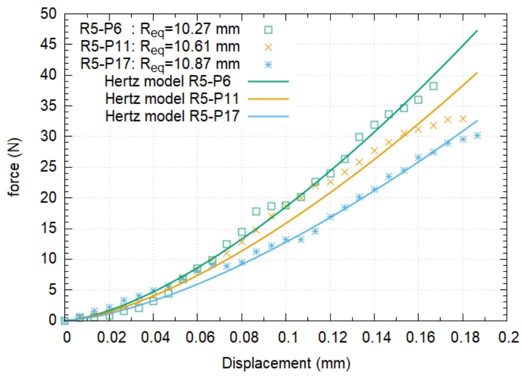

Fig. 5 Example of fitting experimental results with the hertz contact model

IV. RESULTS AND DISCUSSION

This section describes the experimental results found from uniaxial compression test performed on 288 individual expanded clay granules. Fig. 6 illustrates an example of the testing results showing the measured force as a function of the applied displacement. The curve shows small drops in the measured force in some instances, which correspond to the failure of small asperities in the contact zone between the grain and the platens. However, the real breakage point is associated by a sudden big drop in the measured force, which quite confirms the brittle behavior of expanded clay grains.

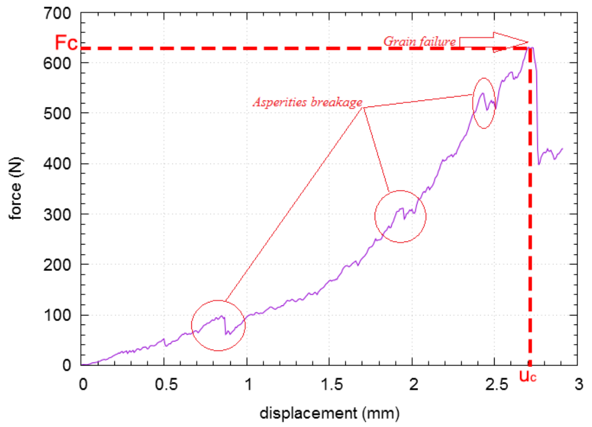

Fig. 6 Example of measured force as a function of applied displacement

To describe quantitatively the crushing phenomenon, the crushing force (F_c) is reported from the force/displacement curve. F_c is used to calculate the associated stress at crushing (σ_c) using Eqn 2. Fig. 7 shows the calculated crushing stress as a function of grain size. It is noticeable that the average grain's crushing strength for each size interval increases with a decrease of its equivalent diameter. For instance, the average crushing strength for the (2, 4) mm size interval is about 4.7 MPa, while it is only 1.6 MPa for the (14, 17) mm size interval. The significant within-size interval variability is also noticed for the crushing stress, which is also attributed to the internal porosity ratio and its distribution. For instance, a 3mm grain can fail at 1.7 MPa or it may have a crushing stress as high as 12 MPa. Furthermore, it was found that two particles might have the same density (same porosity) and the same size, but with different crushing strengths. For example, the grain R5-P18 (A) and R5-P20 (B) have approximately the same density (0.430 g/cm^3 and 0.429 g/cm^3, respectively) and similar diameters (10.87 mm and 10.92 mm, respectively) but ended up with different crushing stresses (0.79 MPa and 1.58 MPa, respectively). Fig. 8 shows the calculated Young modulus as a function of grain size. There is a significant decrease of the average Young modulus with an increase in grain size.

A power law is suggested in this part to model the experimental results of the uniaxial compression tests. This model is described by the Eqn 4 where σ is the particle's crushing stress, a and b are the fitting parameters.

$$\sigma = a \times R^b \quad (4)$$

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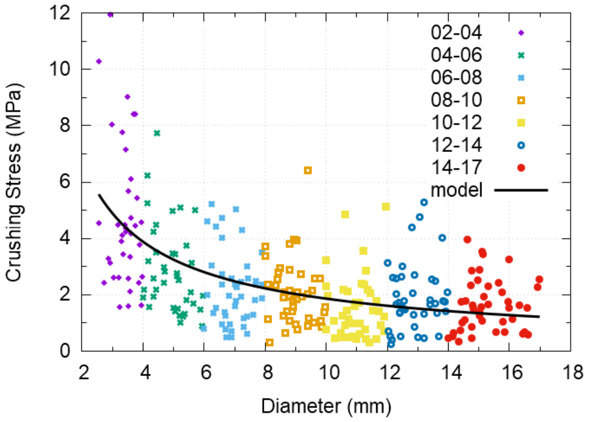

Fig. 7 Crushing stress scatter plot for all tested LECA

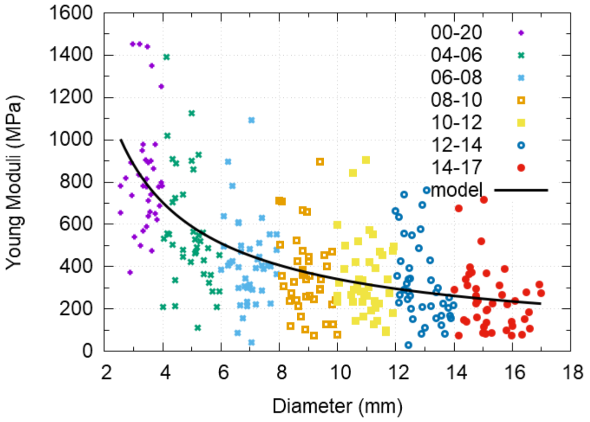

Fig. 8 Young moduli scatter plot for all tested LECA

The average values of all the described results alongside with the number of tested particles for each dimension range are summarized in the Table 3.

Table 3 Average values of expanded clay's studied parameters.

Fraction (mm)	R_{eq} (mm)	E (MPa)	σ_c (MPa)	Tests
2-4	3.40	827. 60	4.74	37
4-6	4.93	561.38	2.85	39
6-8	6.96	421.06	2.214	43
8-10	8.95	353.17	2.081	42
10-12	10.98	342.14	1.533	42
12-14	12.87	321.22	1.882	42
14-17	15.29	244.38	1.625	43

The suggested model shown a good agreement with the experimental results with a correlation coefficient equals to 0.55 for the crushing stress and 0.62 for the Young moduli.

Results for the fitting parameters are presented in table 4.

Table 4 Fitting parameters for crushing stress and Young moduli.

Fraction (mm)	E	σ_c
a (MPa)	2100.12	11.789
b	-0.789	-0.801

V. CONCLUSION

The characterization of the crushing behavior of expanded clay is the main idea of this paper. An experimental investigation was carried out to determine the physical and mechanical properties of this complex material (individual grains) under uniaxial compression test. The mechanical behavior of the individual grain was experimentally studied by measuring the crushing stress and the Young moduli determined using the uniaxial compression tests results. These results have shown a random distribution of the crushing stress and Young moduli which are well correlated to the particle's dimension using a power law. The suggested law shows a good agreement with the experimental results.

All these results from the experimental campaign will be used in further investigations to simulate the macroscopic grains assembly behavior of expanded clay in order to give a guideline for the engineering consulting to properly design the works using such material.

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AUTHORS PROFILE

Haithem Ben Jamaa is a Tunisian researcher in the geotechnical engineering field. He graduated from the National Engineering School of Gabes as a civil engineer. He started his research experience with a project in the National Mining School of Paris (MINES-PARISTECH) where he studied the behavior of grouted reinforcing glass fiber bars on the cutting edge of conventionally excavated tunnels. Currently he is a civil engineering PhD student at the National engineering School of Tunis, Tunis El-Manar university. His research mainly focuses on studying the behavior of granular materials used in geotechnical engineering based on experimental tests and numerical simulations with the Discrete Elements Method.

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