Stress-path effects on the grading of an artificial material with crushable grains

Stress-trajectoire effets sur le granulométrie d'un matériau artificiel avec des grains déformables

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ABSTRACT: Granular materials forming natural slopes, embankments, foundations, pavement structures, and rail track structures are subjected to static and dynamic loads, which may cause particle breakage to occur. Results are presented of an experimental investigation into the mechanical response of an artificial granular material, consisting of crushed expanded clay pellets, commercially known under the brand name LECA (Light Expanded Clay Aggregate) to various stress path tests. The material was reconstituted, with a maximum particle size of 2 mm, to obtain grading curves with the same mean diameter d_{50}, and different coefficients of uniformity, U (= 3.5, 7, 14, 28) or the same U and a different d_{50} (= 0.5, 1 mm). The constant volume friction angle and the minimum and maximum densities corresponding to each grading were determined before stress path testing in one dimensional and triaxial compression at different stress levels. Changes in the LECA grading after the stress path tests were described using two parameters defined respectively as the mean diameter and coefficient of uniformity of the final distribution over the value of the initial distributions, both of which were assumed to be consistent with self-similar grading with varying fractal dimension.

RÉSUMÉ: Les matériaux granulaires formant des pentes naturelles, des talus, des fondations, des structures de chaussées et des structures de voie ferrée se sont soumis à des charges statiques et dynamiques, qui peuvent causer la rupture des particules de se produire. Les résultats sont présentés sur une recherche expérimentale sur le comportement mécanique d'un matériau granulaire artificielle, composée de boulettes d'argile expansée concassées, commercialement connu sous le nom de marque LECA (Light agrégat d'argile expansée) à différents tests chemin de stress. Le matériau a été reconstituée, avec une granulométrie maximale de 2 mm, pour obtenir des courbes de gradation avec le même diamètre moyen d_{50}, et différents coefficients d'uniformité, U (= 3,5, 7, 14, 28) ou même U et une autre d_{50} (= 0,5, 1 mm). L'angle de volume constant de friction et les densités minimale et maximale correspondant à chaque classement ont été déterminés avant le test dans un chemin de contrainte de compression triaxiale dimensions et à différents niveaux de contrainte. Les changements dans le classement LECA après les essais de chemin de stress ont été décrits en utilisant deux paramètres définis respectivement comme le diamètre moyen et le coefficient d'uniformité de la distribution finale au-dessus de la valeur des distributions initiales, qui étaient tous deux censés être compatibles avec auto-similaire classement avec plus ou moins la dimension fractale.

KEYWORDS: artificial material, grain crushing, grain size distribution, breakage, stress path testing.

INTRODUCTION

Particle breakage describes the response to loading in which soil particles become smaller, while other mechanisms of deformation, such as slippage, dilation and creep occur. Degradation processes associated with loading-induced grain crushing affect the macroscopic mechanical behaviour of granular materials. For a given material, breakage is affected by both stress level and stress path direction and can cause volume loss leading to settlements and a reduction in the hydraulic conductivity, as finer particle fractions fill voids. Moreover, elastic and frictional properties of the soil are modified due to changes in grain size distribution. Understanding the mechanisms of grain crushing is therefore crucial, as this affects the stress-strain response of the soil under loading.

Different measures have been suggested to quantify the amount of particle breakage in a sample of granular material. Hardin (1985) introduced the relative breakage, B_r, based on the relative position of the current cumulative particle size distribution from the initial cumulative distribution and a cut-off value of 'silt' particle size (of 0.074 mm). The use of the latter implied that all particles would eventually become finer than the (arbitrary) cut-off value in the fragmentation process. This denies the growing understanding that the grain size distribution of an aggregate of any initial grading, under large confining pressure and extensive shear strains, tends to become self-similar (fractal) (Turcotte, 1986; McDowell and Bolton, 1998).

Several studies (*e.g.*: Sammis *et al*., 1987; Tsoungui *et al*.; 1999) have shown that the main effect of particle crushing is to increase the proportion of fine material without significantly changing the size of the largest particles. Larger particles are cushioned by surrounding smaller particles (Imre *et al.,* 2010; 2011), making them more resistant to crushing and giving them a higher coordination number, which is defined as the number of the particle's nearest neighbours. Smaller particles, with smaller coordination numbers, are more likely to be crushed in the fragmentation process. In other words, the cushioning effect due to the large coordination number for larger particles outweighs the effect of reducing strength with increasing particle size (Casini and Viggiani, 2011; Casini *et al.,* 2013).

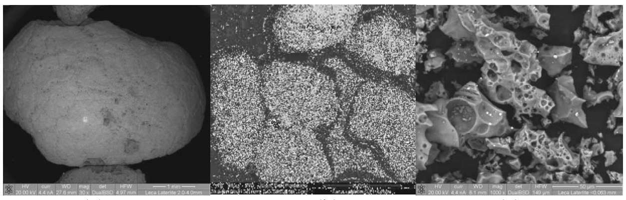
Methods and the results are presented for an experimental investigation on an artificial granular material under different loading conditions. In particular, the paper explores the evolution of the main physical properties, such as the angle of friction and the range of voids ratio together with the grading, sphericity and angularity of the particles under different loading conditions.

For practical reasons, the experimental programme was carried out on an artificial granular material, which was reconstituted at different initial grading with grains that crush at relatively low stress. Samples of the artificial, 'crushable', granular soil, have been subjected to different effective stress paths in one dimensional and triaxial compression, in order to understand the mechanisms of grain crushing better.

1. MATERIAL TESTED

A systematic experimental investigation of grain crushing for natural materials is often difficult due to the relatively high stress required to crush the grains and the variability and heterogeneity of natural deposits, which makes it difficult to obtain repeatable results. For these reasons the experimental work was carried out on an artificial granular material.

The material used is commercially available under the acronym LECA (Light Expanded Clay Aggregate) and is obtained through an industrial process. The expanded clay pellets are screened into their various fractions and made commercially available both as intact (so-called "granular") with a characteristic a round shape and a hard outer shell (see Fig. 1a), or crushed, at different grain sizes (see Figs 1b-c).



(a) (b) (c)

Figure 1. LECA pellets whole/broken with particle diameters: (a) d=2-4 mm; (b) 0.71-1 mm; (c) d<0.063 mm (Wanninger and Zwicker, 2010).

The material has a very low apparent unit weight; this is because the particles are characterised by the existence of a double order of porosity: "inter-granular", i.e. voids existing between particles, and "intra-granular", i.e. closed voids existing within individual particles (see Fig. 2). Because of the voids existing within the particles, their apparent unit weight, γ_s, depends on their diameter d as $\gamma_s(d) = a \cdot (d_0/d)^{b}$, with a = 12.64 kN/m^3, b = 0.268, and d_0 =1 mm (Casini *et al.,* 2013).

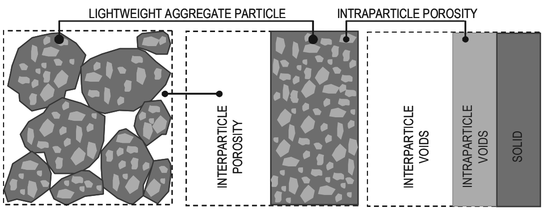


Figure 2. Inter-granular and intra-granular porosity (after Casini and Viggiani, 2011).

1.1 *Initial grading*

The maximum particle size of the tested material was 4 mm; the material was reconstituted to obtain grading curves with the same mean diameter d_{50}, and different coefficients of uniformity, U (= 3.5, 7, 14, 28) or the same coefficient of uniformity, U and different d_{50} (= 0.5, 1 mm) (Figure 3).

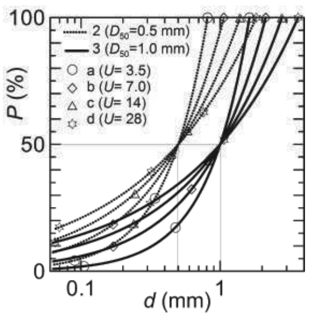


Figure 3. Grain size distributions of reconstituted LECA samples.

1.2 *Basic properties*

The constant volume friction angle φ'$_{cv}$, and the minimum and maximum densities corresponding to each grading were determined before testing. φ'$_{cv}$ was obtained by pouring the material on a rough, flat surface from a given height, and measuring the slopes of the resulting granular cone. The experimental values of φ'$_{cv}$ (Fig. 4) are in the range of 30-33° and increase slightly with the coefficient of uniformity. There is no obvious dependence on the mean grain size.

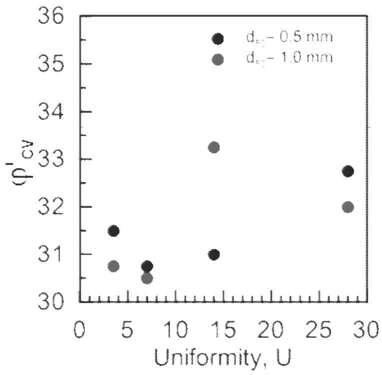


Figure 4. Constant volume angle of friction as function of uniformity for crushed LECA

The maximum (e_{max}) and minimum (e_{min}) voids ratio were determined using non-standard procedures so that particle crushing would not falsify the results. In particular, e_{min} was obtained vibrating the samples with very low input energy.

The experimental values of (e_{max}-e_{min}) obtained for the granular material (Fig. 5) at different values of U and d_{50}, of the order of 0.9 ÷ 1.0, are much larger than those obtained for other granular materials with grains that do not exhibit significant intra-porosity, such as natural river sands, lightweight aggregates and glass ballottini (*e.g.* Miura *et al.,* 1997). LECA can probably be reconstituted at very high values of voids ratio due to the rough surface of the particles of crushed material, as shown in Figure 1, which causes a very "open" structure with loads carried by arching between particles, some of which are effectively unloaded or redundant, and large inter-porosity.

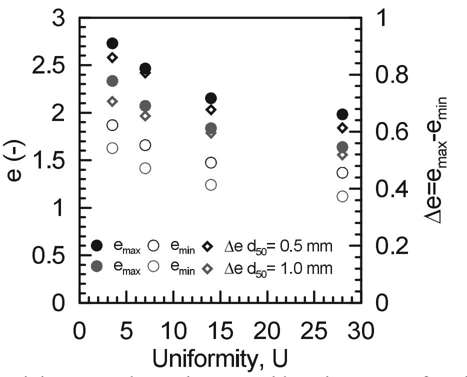


Figure 5. Minimum and maximum void ratios as a function of uniformity for crushed LECA

1.3 *Microstructural features*

Examples of Scanning Electron Microscopy (SEM) micrographs of crushed LECA particles of different dimensions are reported in Figure 6a-b. SEM micrographs of portions of grains belonging to different fractions were manipulated using the image editing program GIMP (Peck, 2008); the exposed intra-granular pores were coloured progressively in black and the contrast in the image was raised until all the pixels were either black (pores) or white (matrix),(compare Figures 6a and

6b). The processed images were then imported in Matlab and the number of white (N_W) and black (N_B) pixels counted with a simple algorithm; it was then possible to attribute the exposed intra-granular porosity of grains, $n_{ei} = N_B/(N_B+N_w)$ to different fractions. Figure 7 shows n_{ei} as a function of particle size, together with the bulk intra-granular porosity, n_{bi} (= $1 - \gamma_{as}/\gamma_s$), obtained from the measurement of the apparent unit weight of particles of different sizes, γ_{as}. The exposed intra-granular porosity is always smaller than the bulk intra-granular porosity as the first is related to the ratio of the average void size to the particle size squared, while the second is related to the same ratio raised to a power 3. Both n_{ei} and n_{bi} increase with increasing grain size, tending to constant values at particle sizes larger than about 3.5 mm, where the apparent unit weight of the particles, $\gamma_{as,}$ becomes constant, with a final ratio $n_{ei}/n_{bi} \cong 1.3$.

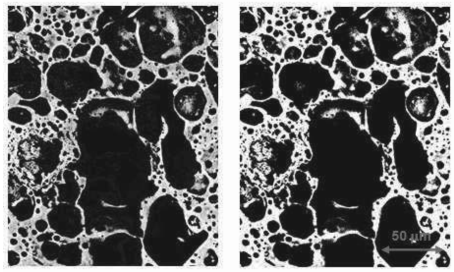


Figure 6. Intra-porosity detected through SEM processing

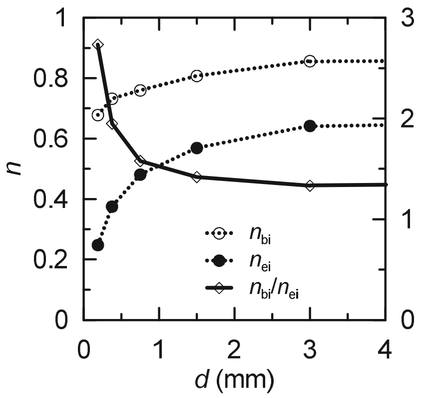


Figure 7. Exposed and bulk intra-granular porosity of crushed LECA particles as a function of grain size.

2 EXPERIMENTAL PROGRAMMEThe samples were subjected to isotropic, one dimensional and triaxial compression (Wanninger and Zwicker, 2010; Leu *et al.,* 2011) at increasing confining pressures (see Fig. 7).

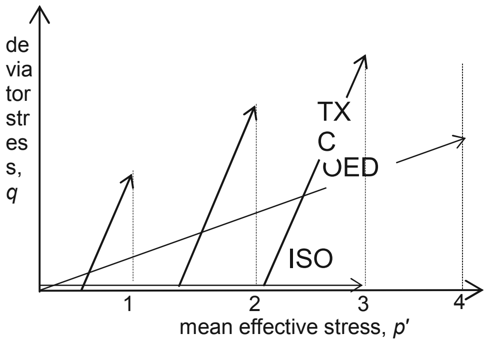


Figure 7. Stress-paths followed in the laboratory tests.

2.1 *Particle sphericity and angularity*

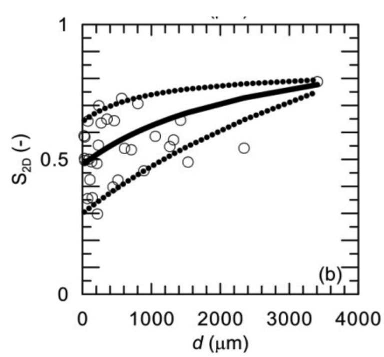


Figure 8. 2D sphericity of crushed LECA as a function of grain size.

SEM micrographs were also used to determine 2D sphericity and angularity of the different fractions systematically. Following the suggestion of Cho *et al.* (2006), 2D sphericity, $S_{2D,}$ was evaluated as the ratio between the diameter of the smallest circle inscribed in the 2D projection of the particle shape and the diameter of a larger circle that contains the whole particle. It is logical that S_{2D} will increase with particle diameter due to surface texture (Fig. 8).

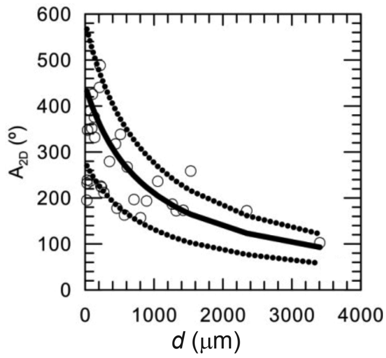


Figure 9. 2D angularity of crushed LECA as a function of grain size.

2D angularity (A_{2D}) of the particles was determined using the definition proposed by Miura *et al.,* 1997. The values of A_{2D} are reported in Figure 9 as a function of particle diameter, where A2D decreases as the particle diameter increases. It should be mentioned that the angularity as evaluated above is a macro angularity of the particles, while further investigations are needed to evaluate the micro-angularity or smoothness of the particles.

2.2 *Evolution of grading*

Figure 8 shows the cumulative grain size distribution by weight obtained for the grading with U = 3.5 and d_{50} = 0.5 mm at increasing mean effective stress. The final grain size distribution (GSD) is rotated upwards and translated leftwards, with an increase of the fine fraction at an almost constant value of the maximum particle size, d_M. The maximum particle size d_M is likely to be different from Δn (maximum dimension of the sieve series) and is unknown, even though d_M must always be less than the sieve dimension Δn. Small changes of d_M with load and stress path are difficult to detect in the laboratory because the spacing of two successive sieves around d_M is finite and not fine enough. The experimental results have been fitted using the equation $P(\%)=(d/d_M)^{\beta}$, represented by the dotted line in Figure 10, which fits the experimental results quite well.

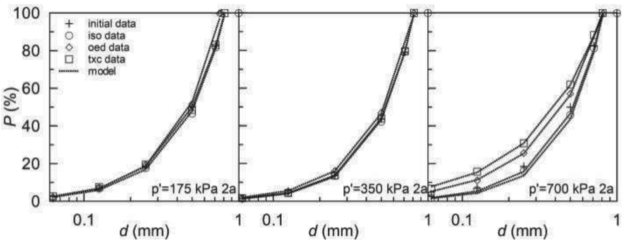


Figure 10. Grain size distribution evolution with U = 3.5 and d_{50} = 0.50 mm.

Grain crushing has been quantified, as a first approximation, using the ratios between d_{50}/d_{50i} and U/U_i, where d_{50i} and U_i represent respectively the initial mean diameter and coefficient of uniformity. Figure 11 (a) and (b) show the evolution for the ratios d_{50}/d_{50i} and U/U_i after 1-D compression for all of the initial GSDs tested, as a function of maximum mean effective stress p'.

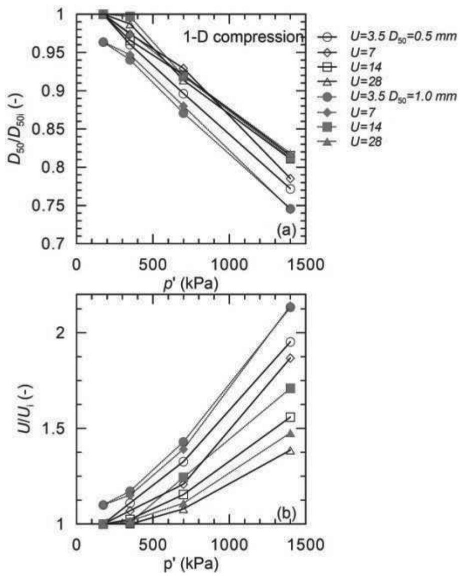


Figure 11. Evolution of ratios: (a) d_{50}/d_{50i} and (b) U/U_i with mean effective stress applied in 1D-compression.

The reduction of d_{50}/d_{50i} with increasing p' is more pronounced for samples with lower initial coefficient of uniformity (U_i = 3.5) and higher mean diameter (d_{50i} = 1 mm). Likewise, as the initial U decreases, the ratio U/U_i increases by a factor greater than 2 for the poorly graded samples with the greater d_{50i}. The ratio U/U_i is consistently higher for higher initial mean diameter (d_{50i} = 1 mm) for all the GSDs tested, which is probably due to the lower coordination number of the particles. The stress acting on the neighbour is higher for the same magnitude and direction of stress applied, as the coordination number decreases, as larger particles tend to be cushioned by surrounding smaller particles. This leads to higher coordination numbers and makes the larger particles more resistant to crushing. Smaller particles, with smaller coordination numbers, are more likely to be crushed in the fragmentation process so that the cushioning effect for larger particles is more relevant than the lower particle strength with increasing particle size.

3 CONCLUSIONS

An extensive laboratory investigation has been conducted on an artificial granular, expanded clay pellets LECA, composed of grains that break at relatively low stresses. These lightweight expanded clay aggregates are used in road construction, tunnelling, structural backfill against foundations, retaining walls and bridge abutments, because of their low unit weight and good drainage properties. In many practical cases, the stress levels to which the material is subjected are comparable to those explored in the present experimental investigation.

The final grain size distribution measured after loading is rotated upwards and translated leftwards (on a standard particle size distribution plot) for all tested samples. The percentage of finer particles increases with increasing mean effective stress and stress-path obliquity. The grain size distributions can be described satisfactorily using simple equations derived from a fractal evolution of grading. Breakage has been quantified as a first approximation through the evolution of non-dimensional ratios of mean diameter and coefficient of uniformity. Poorly graded samples show more pronounced decrease in mean diameter and increase of uniformity with higher stress applied.

Further investigations will be undertaken to reproduce the observed behaviour through a constitutive model to account for breakage and its effects on mechanical behaviour.

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REFERENCES

Casini, F. and Viggiani, G.M.B. (2011). Experimental investigation of the evolution of grading of an artificial material with crushable grains under different loading conditions. *Proc. Int. Symp on: Deformation Characteristics of Geomaterials*, IS-Seoul 2011, 957-964.

Casini F., Viggiani G.M.B. and Springman S.M. (2013). Breakage of an artificial crushable material under loading. *Granular Matter* (submitted).

Cho G., Dodds J. and Santamarina J. (2006). Particle Shape Effects on Packing Density, Stiffness, and Strength: Natural and Crushed Sands. *J. Geotech. Geoenviron. Eng.*, 132(5), 591–602.

Hardin, B.O. 1985. Crushing of soil particles. *Journal of Geotechnical Engineering*, ASCE 111(10), 1177–1192.

Imre B., Laue, J. and Springman, S.M. (2010). Fractal fragmentation of rocks within sturzstroms: insight derived from physical experiments within the ETH Geotechnical Drum Centrifuge. *Granular Matter* 12(3): 267-285. DOI: 10.1007/s10035-009-0163-1.

Imre B., Wildhaber, B. and Springman, S.M. (2011). A Physical Analogue Material to Simulate Sturzstroms. *IJPMG*. 11(2): 69–86. doi:10.1680/ijpmg.2011.11.2.69

Leu J., Low B. and Zimmermann (2011). Effects of grain size distribution and confining stress on the mechanical behaviour of an artificial crushable material *Project thesis*, ETH Zurich, Switzerland.

McDowell, G.R. & Bolton, M.D. (1998). On the micromechanics of crushable aggregates. *Géotechnique* 40(5): 667–679.

Miura, K., Maeda, K., Furukawa, M. and Toki, S. (1997). Physical characteristics of sands with different primary properties. *Soils and Foundations* 37(3): 53-64.

Peck, A. (2008). *Beginning GIMP: From Novice to Professional*, Second Edition. Apress, 548 pp.

Wanninger F. and Zwicker P. (2010). Effects of grain crushing on compressibility of an artificial material. *Semester Thesis*, ETH Zurich, Switzerland.

Sammis, C.G., King, G. and Biegel, R. (1987). The kinematics of gouge deformations. *Pure Appl. Geophys.* 125, 777–812.

Tsoungui, O., Vallet, D. and Charmet, J.C. (1999). Numerical model of crushing of grains inside two-dimensional granular materials. *Powder Technology*, 105(1-3), 190-198.

Turcotte, D.L. 1986. Fractals and fragmentation. *J. of Geophysical Research* 91(B2): 1921–1926.