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 part of natural slopes, embankments, foundations, pavement structures, and rail track structures are subjected to both static and dynamic loads. As a result of this particle breakage may occur. This work shows the results of an experimental investigation into the mechanical behaviour of an artificial granular material, consisting of crushed expanded clay pellets, commercially known under the brand name LECA (Light Expanded Clay Aggregate). The maximum particle size of the material tested was 2 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). The constant volume friction angle and the minimum and maximum densities corresponding to each grading were determined before testing in one dimensional and triaxial compression at different stress levels. The changes of grading of the material after testing were described using two parameters defined as the ratio of the mean diameter and coefficient of uniformity of the current particle size distribution and initial distribution, which were both assumed to be consistent with self-similar grading with varying fractal dimension.

RÉSUMÉ : Les matériaux granulaires qui font partie de la pente naturelle, digues, fondations, structures de chaussées et des structures de voie ferrée se sont soumis à la fois aux charges statiques et dynamiques. À la suite de cette rupture des particules de charges peut se produire. Ce travail présente les résultats d'une étude expérimentale sur le comportement mécanique d'un matériau granulaire artificielle, composée de boulettes d'argile expansée concassées, plus communément connus sous le nom de marque LECA, comme un acronyme pour granulats d'argile expansé léger. La taille maximale des particules du matériau testé est de 2 mm, le matériau a été reconstitué à obtenir des courbes de gradation avec le même diamètre moyen D_{50}, et différents coefficients d'uniformité, U (= 3.5, 7, 14, 28) ou le même coefficient d'uniformité , U et D_{50} différent (= 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 l'essai dans une compression triaxiale dimensions et à différents niveaux de contrainte. Les changements de classement du matériau après les essais ont été décrites à l'aide d'un seul paramètre en fonction du rapport des aires sous la granulométrie et la répartition limitant, qui ont tous deux été supposé être compatible avec auto-similaire classement avec plus ou moins la dimension fractale.

KEYWORDS: artificial material, grain crushing, grain size distribution, breakage.

1 INTRODUCTION

Particle breakage is a phenomenon where the soil particles transform to finer state while other mechanism of deformation under load, such as slippage, dilation and creep occur under loading. The degradation processes associated with loading-induced grain crushing and debonding affect the macroscopic mechanical behaviour of granular materials. Particle breakage causes settlements and a reduction in the hydraulic conductivity. Moreover, elastic and frictional properties of the soil are modified as a consequence of the changes in grain size distribution. Understing 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 breakage undergone by a sample of granular material. Hardin (1985) introduced the relative breakage, B_r, based on the relative position of the current cumulative 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, in the fragmentation process, all particles will eventually become finer than the (arbitrary) cut-off value. This conflicts with the growing understanding that the grain size distribution of aggregates of any initial grading, under extremely large confining pressure and extensive shear strains, tends to a self-similar (fractal) distribution (Turcotte, 1986; McDowell and Bolton, 1998).

Several studies (*e.g.*: Sammis *et al*., 1987; Tsoungui *et al*.; 1999) have confirmed that the predominant effect of particle crushing is to increase the proportion of fine material without particularly changing the size of the largest particles. This has been explained with the tendency of larger particles to get cushioned by surrounding smaller particles, which gives them higher coordination numbers and makes them more resistant to crushing. 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).

This work presents the results of an extended experimental investigation on an artificial granular material under different loading condition. In particular, the evolution of the grading of the material under different loading conditions is experimentally investigated. The experimental programme has been carried out on an artificial granular material with grains that crush at relatively low stress, which has been reconstituted at different initial grading. For a given material, particle breakage is affected by both stress level and stress path direction. In order to understand better the mechanisms of grain crushing, samples of the artificial granular soil with crushable grains, have been subjected to different effective stress paths using existing oedometer and triaxial apparatuses.

2 TESTED MATERIAL

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 consisting of crushed expanded clay pellets, whose grains break at relatively low stress. The material used is commercially available under the acronym LECA (Light Expanded Clay Aggregate) and is obtained through an industrial process.
The clay is extracted from relatively shallow mines and then homogenized, moistened, and broken up with grinding equipment and rolling mills. The main phase of the production cycle takes place in a long rotary kiln. The clay enters the kiln from one end and moves along it, gradually increasing its temperature. At the other end of the kiln the temperature reaches approximately 1200 °C, at which point the clay is in a molten state and the expansion process commences providing a cellular vitreous interior to each pellet. Rolling of the pellets within the kiln gives them a round shape and creates a hard outer shell (see Fig. 1a). The expanded clay pellets are then screened into their various fractions and made commercially available both as intact (so-called "granular") or crushed, in different grain sizes (see Figs 1b-c).

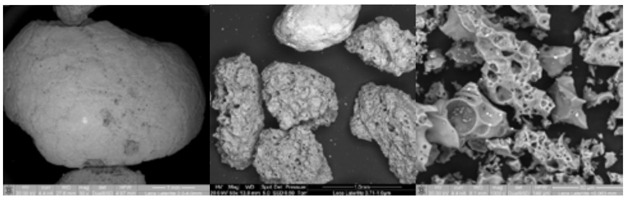

Figure 1. LECA pellets whole/broken with different size: (a) d=2-4 mm; (b) 0.71-1 mm; (c) d<0.063mm (after Pascal and Wanninger 2010).

The main physical characteristic of the material is the very low apparent unit weight of the particles; this is due to 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).

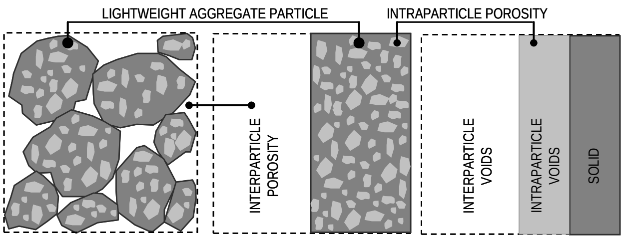

Figure 2. Inter-granular and intra-granular porosity (after Casini and Viggiani 2011).

The apparent unit weight of the particles depend on the diameter d of particle thorugh the equation $\gamma_s(d)=a\cdot(d_0/d)^{b}$ where d is the diameter particle with a=12.64 kN/m^3, b=0.268 d_0=1mm (Casini *et al* 2013).

1.1 *Initial grading*

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

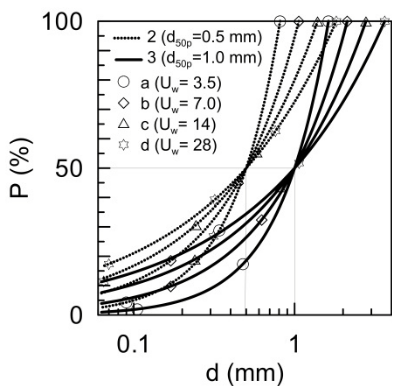

Figure 3. Grain size distribution tested.

1.2 *Basic properties*

The constant volume friction angle and the minimum and maximum densities corresponding to each grading were determined before testing.

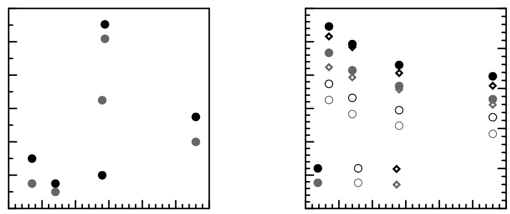

Figure 4. Constant volume friction angle; b) minimum and maximum void ratios function of uniformity for crushed LECA

The maximum and minimum voids ratio were determined using non-standard procedures meant to avoid further crushing; in particular the minimum voids ratio was obtained vibrating the samples at very low energy. The experimental values of (e_{max}-e_{min}) obtained for the granular material 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 permanent grains, including natural sands, light weight aggregates and glass ballottini (*e.g.* Miura *et al* 1997). These very high values of voids ratio at which it is possible to reconstitute the material are probably due to the very rough surface of the particles of crushed material as shown in Figure1, which favours a very "open" structure.

1.3 *Microstructural features*

In Figure 5(a) to (f) are reported examples of Scanning Electron Microscopy (SEM) micrographs of crushed LECA particles of different dimensions. 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), see Figure 5. 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; in this manner it was possible to work out the exposed intra-granular porosity of grains belonging to different fractions, n_{ei} = $N_B/(N_B+N_w)$. Figure 7 shows n_{ei} as a function of particle size, together with the bulk intra-granular porosity, obtained from the measurement of the apparent unit weight of particles of different sizes, n_{bi} (= 1 − γ_{as}/γ_s). The exposed intra-granular porosity is always larger 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 $n_{ei}/n_{bi} \cong 1.3$.

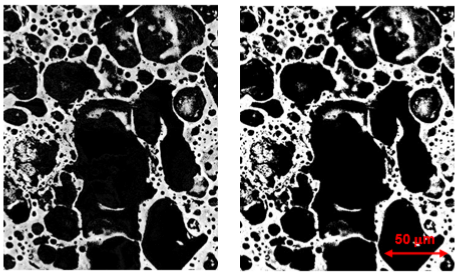

Figure 5.Intra-porosity detected through SEM processing

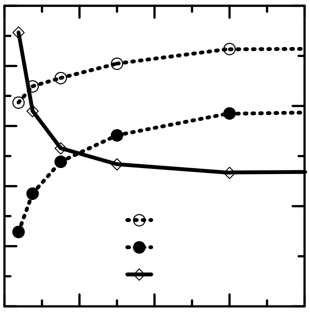

Figure 6. Exposed and bulk intra-granular porosity of crushed LECA particles as a function of grain size.

2 EXPERIMENTAL RESULTS*Stress path*

The samples has been tested under isotropic, one dimensional and triaxial compression test (Pascal and Wanninger 2010; Leu, Low and Zimmermann 2011) at increasing confining pressures, on samples of each of the reconstituted grain size distributions (see Fig. 7).

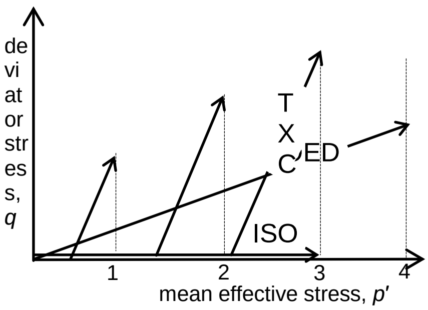

Figure 7. Stress-path followed in the laboratory test.

2.2 *Experimental results*

Figure 8 show 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. It has to be noted that the maximum particle size d_M is likely to be different from Δn (maximum dimension of the sieve series) and unknown, even if, of course, $d_M \leq \Delta n$. Small changes of d_M with load and stress path are difficult to detect in the laboratory because the spacing of two following sieves around d_M is finite and not fine enough. The experimental results has been fitted using the equation $P(\%)=(d/d_M)^{\beta}$ represented by dotted line in Figure 8, which fits quite well the experimental results.

Table I. Experimental programme (after Casini *et al* 2013) grain size distribution by weight

type	initial grading*			p'_{max} (kPa)			
		U	D_{50} (mm)	1 175	2 350	3 700	4 1400
ISO	2a	3.5	0.50	●	●	●	
ISO	2c	14	0.50	●	●		
ISO	2d	28	0.50	●	●		
ISO	3a	3.5	1.00	●	●		
ISO	3c	14	1.00	●	●	●	
ISO	3d	28	1.00	●	●	●	
OED	2a	3.5	0.50	●	●	●	●
OED	2b	7	0.50	●	●	●	●
OED	2c	14	0.50	●	●	●	●
OED	2d	28	0.50	●	●	●	●
OED	3a	3.5	1.00	●	●	●	●
OED	3b	7	1.00	●	●	●	●
OED	3c	14	1.00	●	●	●	●
OED	3d	28	1.00	●	●	●	●
TXC	2a	3.5	0.50	●		●	
TXC	2c	14	0.50	●	●	●	
TXC	2d	28	0.50	●	●	●	
TXC	3a	3.5	1.00	●	●	●	
TXC	3c	14	1.00	●	●	●	
TXC	3d	28	1.00	●	●	●	

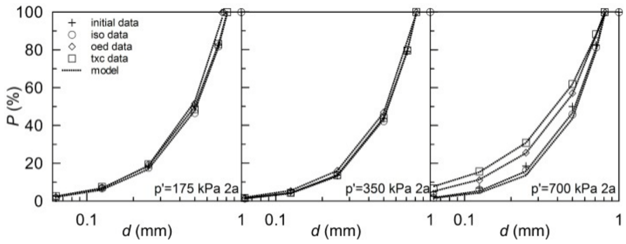

Figure 8. Grain size distribution evolution with U_w=3.5 and D_{50}=0.50 mm

The grain crushing has been quantified, as a first approximation, using the ratios between D_{50}/D_{50i} and U/U_i, where D_{50} and U_i represent respectively the initial initial mean diameter and coefficient of uniformity. Figure 9 (a) and (b) show the evolution for the D_{50}/D_{50i} and U/U_i after 1-D compression for all the intial grading tested as a function of maximum mean effective stress p'.

The reduction of D_{50}/D_{50i} with increasing mean effective stress are more pronounced for samples with lower initial coefficient of uniformity (U_i=3.5) and higher mean diamater (D_{50i}=1mm). As the initial U decreases, the ratio U/U_i incresases becoming higher than double for samples poor graded. Consistently, for all the grading tested, the ratio U/U_i is higher for higher initial mean diameter (D_{50i}=1 mm).

This should be due to the lower coordination number of the particles , defined as is the number of its nearest neighbours. For the same magnitude and direction of stress applied, the stress acting on the neighbour is higher as the coordination number decreases. This has been explained with the tendency of larger particles to get cushioned by surrounding smaller particles, which gives them higher coordination numbers and makes them more resistant to crushing. 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.

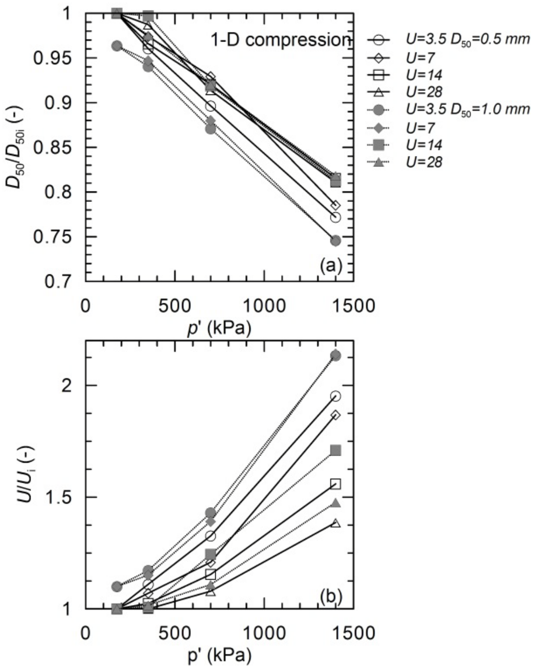

Figure 9. Evolutuiont of ratios: (a) D50/D50i and (b) U/Ui with mean effective stress applied in 1D-compression

3 CONCLUSION

An extensive laboratory investigation has been conducted on an artificial granular, expanded clay pellets LECA, whose grains break at relatively low stress. 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 mainly for all tested samples, with an increases of finer particles with increasing mean effective stress and obliquity. The grain size distribution are satisfactory described with a simple equations assuming a fractal evolution of grading. As first approximation, the breakage has been quantified through the evolution of adimensional mean diameter and coefficient of uniformity. Poorly graded samples shows more pronounced decreasing of mean diameter and increasing of uniformity with higher stress applied.

Further investigation will be done to reproduce the observed behaviour thorugh a constitutive model accounting for breakage and its effects on the mechanical behaviour of the tested material.

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