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Water retention properties of perlite as a material with crushable soft particles

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ABSTRACT

The purpose of this study is to present and discuss the experimental results of the water retention properties of an unsaturated material with crushable soft particles. Perlite was used as an artificial material due to its highly crushable behaviour on loading. In this study an approach including crushing and soft behaviour of the particles and its effect on water retention characteristics is specially proposed. The crushing effect of perlite grains is shown by the evolutions of the grain size distribution curves. The usefulness of the Weibull theory for perlite material, in order to predict the grain-size curves after the crushing, is highlighted. Using different experimental techniques on partially saturated perlite, a first insight into the water retention characteristics of the material is presented. The effect of the double porosity on water retention curve of the material is also highlighted. The evolution of the water retention characteristics with crushing is analysed, by using the Aray and Paris model in conjunction with the Weibull distribution predictions. Predicted and experimental results are compared and discussed.

1. Introduction

The hydraulic behaviour of unsaturated materials can be expressed by means of the water retention curve (WRC), as a relationship between the negative pore pressure (suction) and the water content (or degree of saturation). It is also linked to the relative water permeability (permeability of unsaturated material), which is often deduced from WRC results by using different empirical models. Experimental results and WRC models for soils have been proposed by neglecting mechanical aspects (Basile and D'Urso, 1997; Arya et al., 1999; Zeiliguer et al., 2000; Vaz et al., 2005). However, the importance of the mechanical response on the water retention characteristics have been recently highlighted, specially by studying the influence of the compaction on the WRC and by coupling the hydraulic and mechanical behaviour (Delage et al., 1996; Romero et al., 1999; Vanapalli et al., 1999; Cuisinier and Laloui, 2004). The conclusions of these studies clearly indicated that when uncoupled hydraulic paths were applied, an important influence of the initial water content and the hydraulic history (drying and wetting) was identified in the water retention properties. On the other hand, when coupled hydraulic and mechanical actions were considered, the loading conditions reflected a larger influence on the water retention characteristics.

For unsaturated compacted soils, it has been shown that the microstructure of a given soil is not unique, and strongly depends on the compaction and hydraulic paths followed (Birle et al., 2008). The initial water content and dry density have an important influence on microstructure, and as a consequence on both the soil water retention and the relative water permeability. Birle et al. (2008) studying Lias-Clay showed a strong influence of compaction water content at values larger than 11–12.5%. This is consistent with the lower permeability detected on soils compacted wet of optimum and usually interpreted by the microstructural changes undergone by the material at elevated water contents (Cuisinier and Masrouri, 2005; Delage, 2006; Romero and Simms, 2008). This is why; understanding microstructural features on water retention properties have gained relevance (Delage et al., 1996; Romero and Simms, 2008), particularly for geo-environmental earth structures design such as landfills, engineered barriers, embankments and dams.

Based on the previous discussion, there is a need to investigate the loading actions and their effects on the evolution of microstructure and their consequences on engineering properties, such as water retention curve, compressibility, water permeability and shear strength (Penumadu and Dean, 2000). In this sense, selecting a proper material with a highly sensitive microstructure to mechanical actions is very useful. However, to the authors' knowledge, most of microstructure investigations have been carried out with undeformable material particles, in which loading actions on microstructure are of limited action affecting only the porosity. In the case of soft and crushable grains, loading actions have a strong influence on both macro and micro voids (Lade et al., 1996). Particularly, the present paper addresses the evolving nature of the water retention properties of a highly crushable material with soft particles when undergoing loading paths.

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In the other hand, many recent researches focused on the study of the hydro-mechanical properties of materials with deformable particles (Bouhlel et al., 2010). In general, the hydro-mechanical deformations don't take into account the fragmentation of the grains. However, for several materials particularly for those used in civil engineering applications (ballast, rocks, expanded clay,…), the grains fragmented under static and cyclic loads (McDowell and Bolton, 1998; Coop et al., 2004). The crushing phenomenon can also be accelerated by the humidity evolution inside the material (Oldecop and Alonso, 2001).

As an example it is the expanded clay (looks like expanded perlite), which is used in many applications because of its lower density. Particularly, it is used for embankment constructed on soft clayey soils. In this case, the crushing of the material under loading leads to the reduction of the safety factor of the embankment by the reduction of the friction angle and the decrease of permeability. This crushing phenomenon of expanded clay is strongly related to its water retention characteristics.

In the other hand, the advantages of perlite as its extremely high retention water and low thermal conductivity make its uses and consequently its production increased. The qualities of lightness and insulation make perlite ideally suited for concrete for roof decks (Barnes, 1962; Lanzón and García-Ruiz, 2007). Perlite is also used in other fields. For example, it is used in oil well cementing to prevent lost circulation of drilling lubrication fluids by bridging openings in the well hole walls. Perlite is also used in filtration, not only in industrial field but also in some engineering geology problems like in underdrain trench or in slope filter drain system. In fact, perlite is incorporated to improve moisture retention, which is critical for the treated water drains for the conveyance system of drainage like geotextile. The underdrain trench can be an option of a downstream flow control facility or stormwater outfall. Many other commercial applications for perlite have been recently developed. These include; rock wool, chemical fertilisers, fillers, paints,…etc. (Sa'ad and Al-Hawbanie, 2010).

Consequently, the study of the capability's use of perlite in these applications constitutes an interesting challenge. Among some related problems to the use of perlite is the one associated to the water retention evolution according to the crushing phenomenon. This is an imported question to be addressed in this manuscript.

As a first step in the current study, the water retention properties of the expanded perlite have been determined at different stress levels to highlight crushing effects. The usefulness of the Weibull theory for perlite material to predict the grain–size curve after the crushing is then discussed. The grain–size curves for different crushing states are then used to predict water retention characteristics based on the Aray and Paris model. The paper ends with a discussion and comparison of the experimental and predicted water retention curves.

2. Tested material

Perlite is a hydrated volcanic glass formed through the secondary alternative of obsidians by the incorporation of water into the glass silica structure. Fig. 1 shows the three main forms, in which perlite may be found from its natural state to its final expanded form. Expanded perlite has a snow-white colour and a maximum water content of 1% at relative humidity of 50%. The bulk density of the raw material is 0.9 to 1.1 Mg/m^3. Extremely low material dry densities for the expanded perlite may be found, such as $\rho_d = 0.35$ to 0.45 Mg/m^3. A value of solid density of 2.1 Mg/m^3 has been determined for highly crushed perlite following NF P94-054 (AFNOR, 1995). This value can be used to estimate volumetric relationships. It is important to indicate that this solid density is strongly affected by the experimental difficulty of eliminating the air volume inside compressible grains. This is why the best determination of this solid density requires to heavily compact the material. In fact, if the grain has an internal void, its solid density is hard to determine because of the difficulty of the volume measure and to extract the water in micro-pores. As an alternative, the use of mercury can be suggested. In fact, mercury is not absorbed by the grains because it has larger molecules which cannot enter the micro-voids of grains. However, as the mercury technique is not actually allowed in laboratory, the density of the heavily compacted material is finally retained as a referential density.

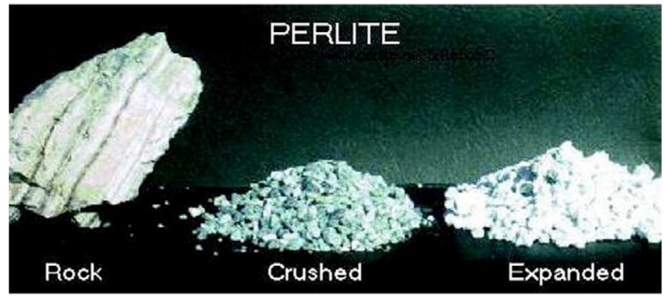

Fig. 1. Perlite aggregate from rock to expanded state.

Fig. 2 presents micrographs showing the porous network, in which two dominant pore sizes are identified: micropores inside grains and macropores between grains. A complementary picture of this network is shown in Fig. 3 using electron photomicrographs, which clearly indicate the double porosity characteristics of perlite and the difference between the average dimensions of the micro (Figure 3a) and macrovoids (Figure 3b). Note that electron-microscope photos of thin sections of expanded perlite support the assumption of internal, cellular structure of the grain (Figure 3a). This double porosity network has been also detected using mercury intrusion porosimetry (MIP), which was also used to gain quantitative information on the double-porosity network of the perlite. MIP tests were performed on 'Micromeritics-AutoPore IV' equipment, attaining maximum intrusion pressures of 220 MPa. The largest and smallest pore sizes that can be measured are 400 μm and 6 nm (through Washburn equation), respectively. MIP tests were performed on compacted perlite at a dry density of 0.25 Mg/m^3 and on a group of uncrushed grains with a slightly lower dry density. Further information on MIP can be found in Romero and Simms (2008). Fig. 4 shows the cumulative intruded void ratio (Figure 4(a)) and the pore size density function (Figure 4(b)) of the compacted perlite with void ratio $e = 7.5$ (intruded void ratio $e = 8.5$), in which two dominant peaks are clearly identified in the density function. The lower dominant pore size corresponds to the apparent diameter inside grains (micropore) with dominant mode at around 2 μm, whereas the larger peak corresponds to the dominant dimension of the inter-grain pores (macropore) with 10 μm. Nevertheless, the large peak is also expected to be affected by the compressibility of the grains. On compression both dominant pore sizes are expected to decrease due to crushing and compression of grains. This is not the case of soils with undeformable grains, in which only the macroporosity is affected on loading due essentially to particle re-arrangement. The figure also incorporates the intruded void ratio and pore size density function of the group of uncrushed grains. Again, the double porosity is well defined with two dominant peaks at similar values to those detected on compacted perlite.

On the other hand, and from a macroscopic point of view, at high compression stresses, grains of expanded perlite cannot be further compressed resulting in a completely reduced void ratio. As it was shown already by Georgopoulos (2006), expanded perlite is a strongly crushable material under moderate stress levels. Fig. 5 shows isotropic tests on expanded perlite. At the same diagram isotropic compression test results from Hostun sand are also given for comparison. At low stresses expanded perlite undergoes severe grain damage and compression, marked by large volumetric strains. At higher stresses,