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A laboratory investigation of the mechanical behaviour of a volcanic ash

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***Abstract* – This paper presents the results of a physical and mechanical characterization of a volcanic ash collected during a recent eruptive episode of Mount Etna. The mineralogy and microstructure of the material are examined by means of X-ray diffractometry and electron scanning microscopy (*SEM*). Because of their lightweight, highly crushable and compressible nature, they are problematic from engineering and construction viewpoint. The laboratory testing programme consisted of standard drained and undrained triaxial compression tests, one-dimensional compression tests and direct shear tests. Herein, data which highlight particle damage during the one-dimensional compression are presented. Using a dynamic image analysis instrument (*QicPic*) the changes to particle size distribution and particle shape through breakage are investigated for samples with different initial densities to examine the effects of particle packing on their behaviour. The amount of breakage is quantified comparing the grain size distributions at the beginning and at the end of each test.**

I. INTRODUCTION

Many granular materials are composed of particles that can be damaged by abrasion, shearing-off of asperities, and splitting rather than flowing plastically under stress. In these materials, plasticity arises primarily from particle damage.

There are also many weak-grained crushable soils, such as decomposed granites, carbonate sands, and volcanic soils, for which particle damage occurs under low confining stresses. Moreover, changes in particle-size distribution due to particle damage may produce more drastic changes in internal structure than those due by particle rearrangement alone [1].

For these reasons, the effect of particle damage on the mechanical behaviour of coarse-grained soils should not be neglected.

The role of particle breakage in defining the constitutive behaviour of granular materials changes the way to interpret their macroscopic behaviour (e.g. [2-4]). The susceptibility of these materials to particle breakage is generally associated with the tensile strength of soil particles.

Usually tensile strength depends on particles size: smaller grains, generally, exhibit higher tensile strengths [e.g. 3,5-6].

There are other factors influencing the probability of particle breakage [5,7-8]. The initial grading of soil is also of key importance in defining the density of sample and then the inter-particle forces that will result from the number of particle contacts. By using discrete element methods (*DEM*) (e.g. [9]) it has been found that well-graded samples exhibited higher coordination numbers and then lower probability of breakage.

Most of recently published experimental results focused on the effects of particle breakage on the location of the Normal Compression Line (*NCL*) and Critical State Line (*CSL*). Bandini and Coop [10] found that the Critical State Line does move with particle breakage, denoting that the soil does “know” about the breakage that has occurred. However, large amounts of breakage were required to create a significant shift.

Comparison with the behaviour of reconstituted samples with the same grading as the pre-sheared samples demonstrated that while the soil does have some “knowledge” that it has undergone breakage, the initial grading remains more important than the current grading in determining its behaviour.

This paper concern with the physical and mechanical characterization of a volcanic ash collected during a recent eruptive episode of Mount Etna. Due to its lightweight, the tested material has highly crushable and compressible nature.

The paper presents data which highlight particle damage during the one-dimensional compression. In order to examine the effects of particle packing, changes to particle size and shape due to breakage are investigated testing soil specimens characterized by different initial densities.

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II. TESTED SOIL

The tested soil is a volcanic ash (the "*Etna sand*") collected during a recent eruptive episode of Mount Etna.

X-ray diffractometry and electron scanning microscopy (*SEM*) were used to analyze the mineralogy and microstructure of *Etna sand*. These analyses showed that the particles are highly vesicular glass shards with a particular angular shape (Fig. 1) resulting from the violent explosive interaction between magma and water. The material is composed by cristobalite and anaorthite. The first is a high-temperature polymorph of silica and is characteristic of the type of eruption that formed the material analyzed. The second is a ubiquitous mineral in all rocks of Mount Etna.

The physical properties of *Etna Sand* are summarized in Table 1 while Figure 2 shows the grading curves.

The laboratory testing programme consisted of standard drained and undrained triaxial compression tests, at increasing values of cell pressure, one-dimensional compression tests, carried out in reduced cross-section oedometers, and direct shear tests.

In this paper only the results of one-dimensional compression tests are presented.

Each soil sample was subjected to high stresses in one-dimensional compression using two types of oedometer cells: a 38 mm and 25 mm diameter cell in testing up to 15 MPa and 35 MPa vertical stress respectively.

Each sample was prepared for testing by dry sieving to separate the soil into its constituent particle size ranges. Samples were then created by mixing soil from each sieve interval in the proportion required for the specific grading of the *Etna Sand*, ensuring that a homogeneous mixture of all the sizes was achieved in each sample. The initial particle size distribution was then checked using the *QicPic* apparatus, which will be described in the following section.

The particle size distributions obtained with the standard (sieving) technique and *QicPic* measurements (using *EQPC* diameter) are compares in Figure 2. The comparison shows some discrepancy arising from the different techniques.

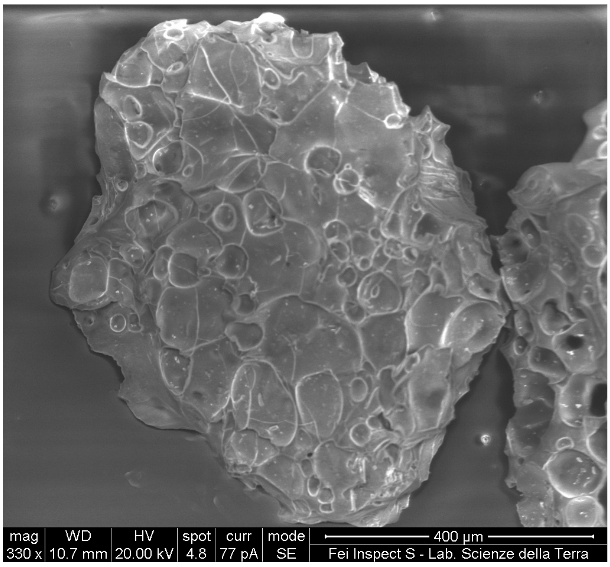


Fig. 1. Scanning electron micrograph of Etna sand at 300X magnification.

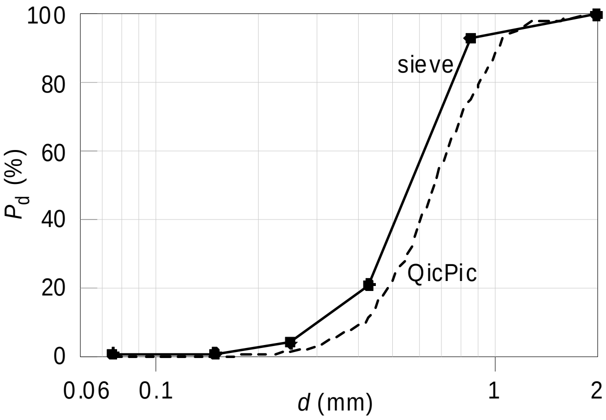


Fig. 2. Particle size distribution of Etna Sand obtained with a standard technique (sieving) and QicPic measurements (using EQPC diameter).

Table 1. Properties of Etna Sand.

D_{50}	0.62
Uniformity coefficient	2.05
e_{max}	2.05
e_{min}	1.27
Estimated specific gravity	2.51
Maximum dry density (kN/m^3)	1.125
Minimum dry density (kN/m^3)	0.839

III. THE QICPIC APPARATUS

The *QicPic* apparatus is a laser image analysis instrument with a manufacturer's stated capacity of measuring sizes between 1 µm and 20 mm.

The *QicPic* uses dynamic image analysis by examining a flow of moving particles. This allows a large sample size to be considered, the particles to be randomly orientated and the occurrence of overlapping particles to be reduced. The dispersing unit creates a well dispersed flow of particles that falls through the scanning beam emitted by a pulsed laser. An exposure time of less than 1 ns ensures that motion blur is not detectable. The laser and the camera detector can operate up to speeds of 500 frames/s, allowing a very large number of particles to be considered in a short duration. Two dispersing units were used with the *QicPic* depending on particle size.

The *GRADIS* is a dry gravity feeding system which is used for particles with sizes between 0.05 and 20 mm and the *LIXELL* is a water circulation system which is used mainly for particles less than 100 µm in size.

The *QicPic* apparatus has an accompanying software which controls the settings of the dispersing unit as well as storing and manipulating the data from measurements. Measurements for each individual particle can be evaluated from its image and this enables a comprehensive analysis of size and shape to be made. Several particle size definitions have been used:

- *EQPC* is the diameter of the equivalent circle with the same area as that of the particle;
- the *aspect ratio* is the ratio between Feret minimum and Feret maximum diameters (i.e the minimum and the maximum distance between two parallel lines which touch the particle on opposite sides in a two-dimensional image);
- the *sphericity* is calculated as the ratio of the equivalent circle perimeter to the real perimeter;
- the *convexity* describes the compactness of a particle as calculated from the ratio of the projected particle area to the gross area including any re-entrant sections.

The accompanying software is able to calculate particle size distributions based on volume or area; the former was chosen here for compatibility with normal soil mechanics practice of using sieved weights.

IV. RESULTS OF ONE-DIMENSIONAL COMPRESSION

The results of the one-dimensional compression tests are shown in Figure 3. A unique *NCL* for this material is clearly defined and is characterized by a compression index (C_c) of 0.784. The unloading response is always stiff, with an average swelling index (C_s) of 0.005.

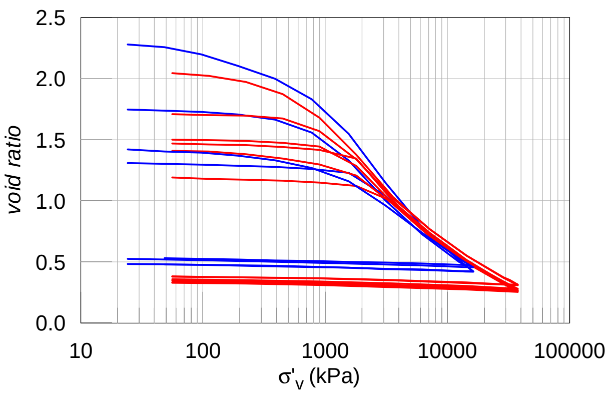
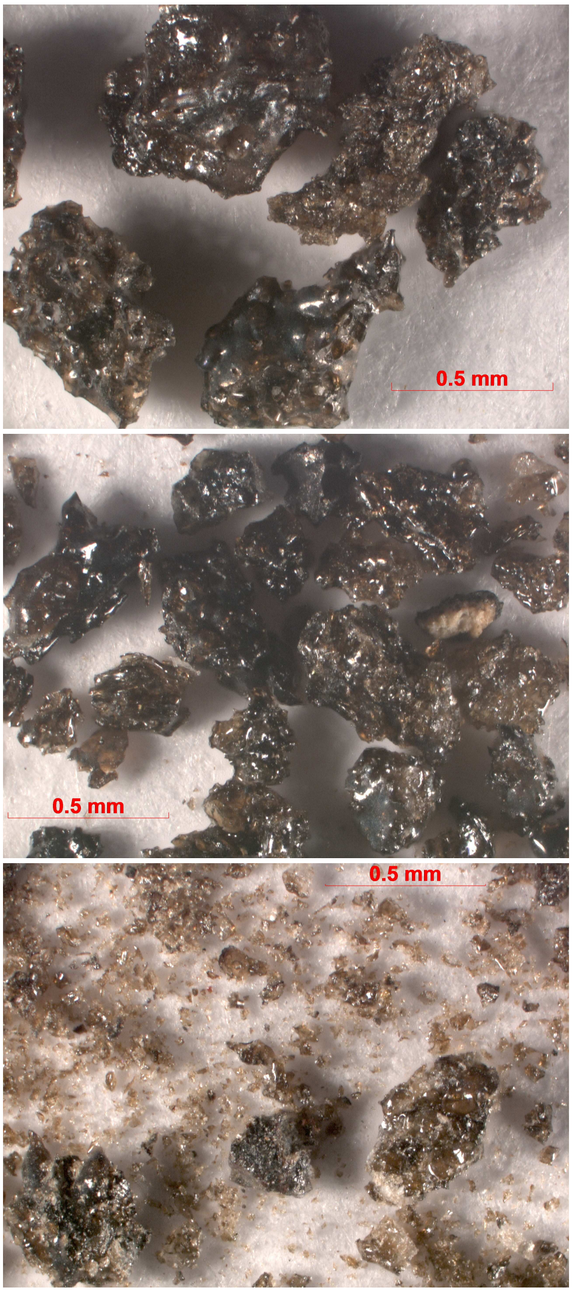


Fig. 3. Compression curves.

Optical microscope images of *Etna sand* samples were taken both before and after one-dimensional compression (Fig. 4). Figure 4a shows that the original sand has sub-angular particles and a narrow range of particle sizes. Figures 4b,c illustrate that compression-induced damage produces a considerable amount of angular to highly angular fine particles, with many fine particles appearing with a lighter colour. The changes in colour is due to the glassy nature of the sand particles.



a)

b)

c)

Fig. 4. Optical macroscope images of Etna sand: before compression (a) and after one-dimensional compression to 15 MPa (b) and to 34 MPa (c).

This microscopic observation fits well with the differences in grain size distribution pointed out by the *QicPic* measurements, at the beginning and at the end of each test (Fig. 5d). Particle damage during compression significantly increased the fines content without changing the maximum particle diameter.

As damage increases with compression, this process results in widening the particle size distribution (i.e., the sand became more well graded), increasing particle coordination numbers and reducing particle contact stresses, thereby reducing potential damage. As expexcted (Fig. 5d) the final grading curves of tests up to 15 MPa vertical stress (red lines) show less breakage than those obtained at the end of the tests which reached 35 MPa (blu lines). Furthermore larger particle breakage occurs in samples with higher initial void ratios.

To quantify the changes in the grading curve the Relative Breakage B_r [11] has been used.

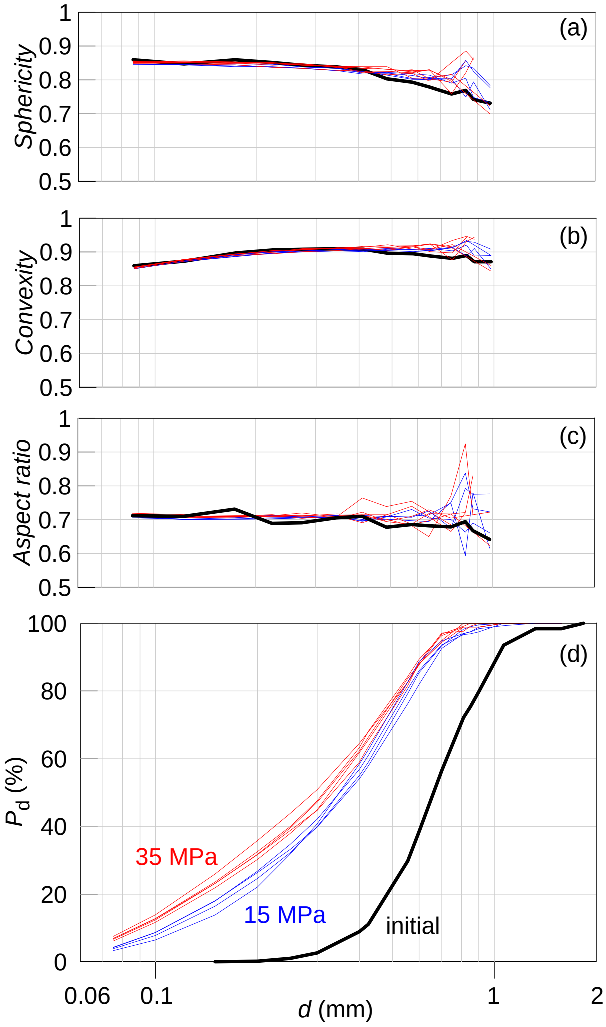


Fig. 5. Morphological parameters (a-c) and particle size distribution (d) computed before (black lines) and after one-dimensional compression to 15 MPa (blue lines) and to 35 MPa (red lines).

B_r evaluates the relative position of the final cumulative distribution from the initial one and an arbitrary cut-off value of 'silt' particle size (of 0.074 mm), indeed the likelihood of particle breakage is greater for larger particles.

Figure 6 shows the relative breakage evaluated for three different void ratio ranges (1.2÷1.3, 1.4÷1.5 and 1.7÷1.8) and vertical stresses from 440 kPa to 35 MPa. Fot the tested sand and for the achieved stress levels, the values of B_r are between 0.5 and 0.6 when vertical stresses are equal to 35 MPa. It is clear that the effect of breakage is significant as early as the lowest stress levels and more important for higher ones. The early yield of the analysed material in compression partially depends on the higher inter-particle forces that will result from the smaller number of contacts due to the lower density. The *Etna Sand* particles are highly vesicular glass shards with a particular angular shape, resulting from the violent explosive interaction between magma and water. Then the samples prepared with different tecnique are always caracterized by very high initial void ratios and therefore are more suscetible to particle breakage. From Figure 6 it can be also noted that, for a given value of the maximum vertical stress reached at the end of the test, the amount of particle breakage is more substantial for specimens made with a higher initial void ratio. This behaviour is evident for values in the stress range 1-9 MPa whicle it is less striking for higher stress levels.

The *QicPic* particle shape analyses in Figures 5(a-c) showed that particles had an initial sphericity and convexity ranging between 0.7-0.85 and 0.85-0.9 respectively and initial aspect ratios of about 0.7. The particles created during compression are more spherical and convex and with higher aspect ratio values than the original particles. However, in all cases the coarser particles remain of similar shape, even though many of the particles are likely to have been damaged by breakage. Measurements of some typical individual particles are given in Figure 7 before and after one-dimensional compression to 15 MPa and to 35 MPa.

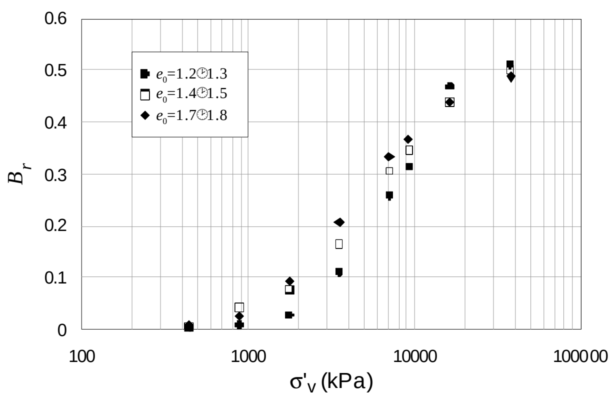
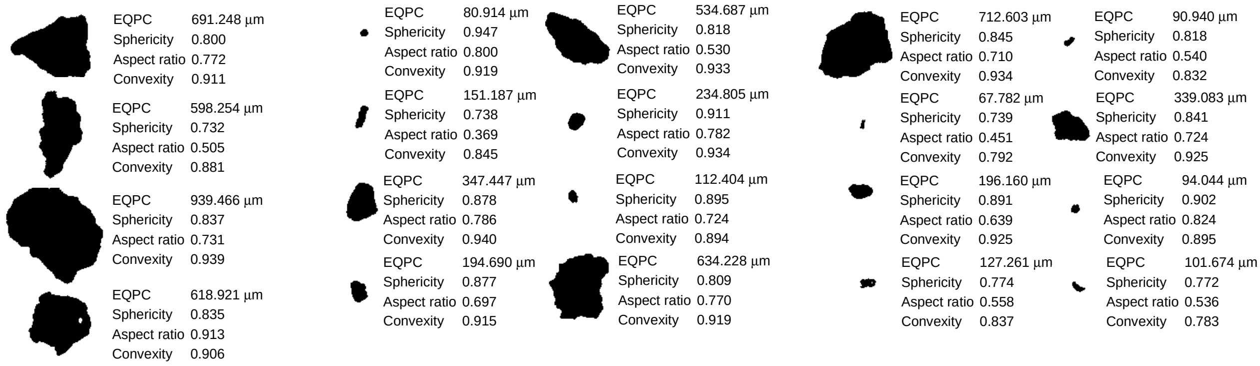


Fig. 6. Particle breakage for Etna sand in one-dimensional compression tests.



(a) (b) (c)

Fig. 7. Examples of particle shapes from the QicPic output for the Etna Sand: (a) before compression; (b) after one-dimensional compression to 15 MPa and (c) after one-dimensional compression to 35 MPa.

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