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Influence of Destructuration on the Compression Behaviour of a Weak Rock

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Abstract: The literature has highlighted the behaviour of several weak rocks and the role of structure in determining them. The need for understanding their behaviour is due to the instabilities or collapse that may involve human settlements built on these materials which are widespread all over the world. In previous studies, the authors highlighted that in Marsala, Sicily, underground calcarenite quarries have been involved in a number of collapses that have seriously damaged numerous overlying buildings. In order to investigate the influence of destructuration on the behaviour of the calcarenite of Marsala, this paper presents a preliminary investigation of the compression behaviour of the intact rock and of the same weak rock in a destructured state. A petrographic and physical characterisation of the material was carried out together with oedometer and isotropic compression tests. The investigation has highlighted behaviour not previously identified for other weak rocks in which the pores seem to play a key role; the destructured material can no longer be considered, as generally assumed for other weak rocks, as a reference.

Keywords: structure; yielding behaviour; weak rocks; stiffness

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1. Introduction

Human settlements built on weak rock deposits are often encountered over the whole Mediterranean area. In the area of Marsala, Sicily, the building material is still collected in large open pit quarries and, as a consequence of urban expansion, quarries of exceedingly large extension were formed, causing conditions of instability because of the poor mechanical properties of the cavity pillars [1]. The rocks outcropping in Marsala are quaternary formations belonging to the sandy silty and calcarenitic system of which the main lithotypes have been identified according to the presence of different spatial arrangements of macropores and micro-pores [2,3].

The Marsala lithotypes are examples of weak rocks, the behaviour of which is strongly affected by structure, which is commonly defined in the literature as a combination of fabric and bonding [4]. In detail, as reported by Folk [5], irregular-shaped calcite grains, which are mainly calcareous and porous, form a network of grains connected by calcite bridges. The material is interpreted as a bonded granular material, in which bonds, according to Ciantia et al. [6], can be subdivided into two classes: the depositional and the diagenetic bonds. These bonds often undergo destructuration processes and so it is important to address the effects of destructuration processes. Therefore, destructuration might be caused by several phenomena occurring in nature (e.g., weathering for saturation and chemical dissolution processes, and mechanical loading). These phenomena can be very complex and multiscale analysis can help in understanding the mechanisms [6].

The mechanical behaviour of weak rocks can be strongly distinguished from soils or hard rocks. It is featured by yield during compression, destructuration processes after yield and modification of yield surface shape [7,8]. Yield results from the degradation of inter-particle bonds and corresponds to the onset of particle crushing, as suggested by Coop [9]. Many authors, e.g., [10,11], observed that, after yield, isotropic compression paths tend to a unique isotropic compression line which is, according to the literature on natural intact soils, the consequence of bond deterioration and an increase in particle crushing. Eventually, as highlighted by Lagioia and Nova [12] for porous weak rocks, the breakage of bonds implies a sudden collapse of the soil skeleton at nearly constant effective stress.

As is known in the literature [13], soil structure effects on soil mechanical behaviour can be studied by comparing the mechanical properties of an intact sample to the same features in its reconstituted state. The difference in void ratio between a compression curve of an intact soil and the corresponding line of the same soil in a reconstituted state, which is usually considered as a reference state, identifies the influence of soil structure at a given mean effective stress p′. For many weak soils, the destructured material can be considered as reference material, e.g., [10,14]. Hence, for these soils, compression lines of the natural samples lie on the left of the correspondent reconstituted material (i.e., positive effect of structure). Despite that, "negative" effects (i.e., compression lines on the left) have been reported for natural highly fissured clayey soils in their reconstituted state, e.g., [15–17]. The results for some natural and artificially cemented calcarenites, e.g., [12] show that unique intrinsic Normal Compression Lines NCLs can be identified when sandy sample behaviour is dominated either by bonding or fabric. When the structure is characterised by high-strength particles and, at the same time, by weak bonds, cemented and uncemented soils show compression lines that run parallelly even if high stresses are reached during loading, e.g., [18]. For sandy soils, no negative effects of the structure, such as those seen for intensely fissured clays, have been observed in any of these cases.

This paper discusses the oedometer test and isotropic compression test results on samples of the Marsala calcarenite at the natural and reconstituted state. In order to characterise the mechanical compression behaviour of the most common lithotype constituting the skeleton of the quarries, although it is poor quality, tests were carried out on the previously investigated lithotype B2, e.g., [3,19]. Particle size distributions, microscope comparisons and micro-computed tomography analyses were carried out on specimens, where possible before and then after the test, in order to identify the role of structure (bonding and/or fabric) and particle crushing in determining the compression behaviour.

2. Materials and Methods

The calcarenites of Marsala were block sampled from an outcrop in situ. As expected, geological and structural features influence the strength and compressibility of the heterogeneous weak rocks, e.g., [3]. As reported in Zimbardo et al. [19], the specimens of lithotype B2 (Figure 1) have a specific gravity Gs of 2.74, the specific volume v_0 is between 1.7 and 2.1 and the mean value of the dry unit weight γd_0 is 13.11 kN/m^3. Initial specific volumes v_0 are based solely on the final dry weights. The almost complete destructuration caused by the high stress levels reached ensured that the error that might be caused by any closed porosity was small. Having been sampled well above the water table in a warm dry climate and being further dried in the laboratory before testing, the differences in specific volumes using the initial and final dry unit weights were in any case small. As reported by Zimbardo [2], the petrographic analyses, which were carried out by means of microscope observation of thin sections, led to the observation of strong bonding and of grains made of bioclasts (96.4%). In addition, lithoclasts were rare. This percentage is the reason why the rock is more appropriately referred to as a biocalcarenite. In decreasing order of quantity, the bioclasts are made of rhodolites, fragments of mollusc shells, foraminifera, rare briozoa, entrocha, an-ellids; the lithoclasts are mainly made of carbonate rock fragments and monocrystalline and, more rarely, polycrystalline grains of quartz silt. The shape and the size of the clasts vary greatly (100 μm to 8 mm) with no preferential grain orientation.

Following the ISRM classification, lithotype B2 can be recognised as an EM soil (a rock of medium deformability and low strength). Deterioration events such as weathering in the natural environment were not present.

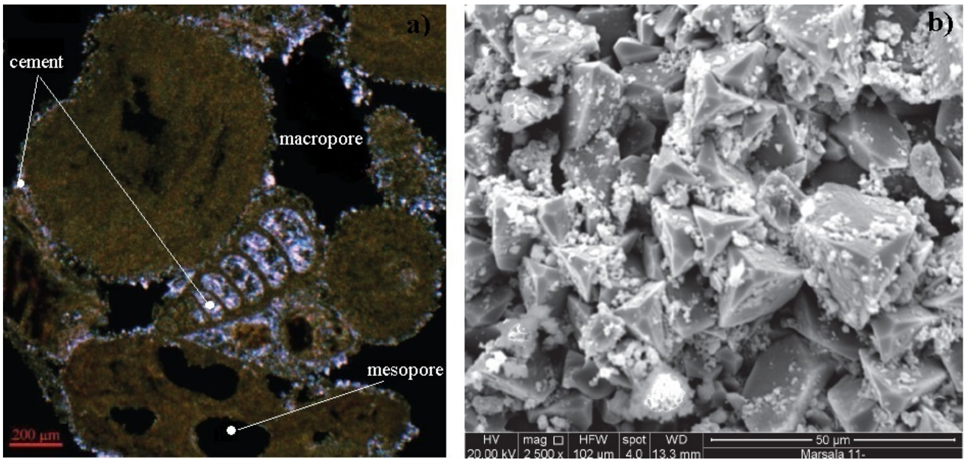

Figure 1. Natural lithotype B2: (**a**) Thin section; (**b**) Environmental scanning electron microscopy image.

In order to investigate the effect of destructuration of this weak rock, the compression behaviour was observed by means of oedometer and isotropic compression tests, as commonly encountered in the literature on this topic, e.g., [14]. For this purpose and in order to compare the effects of the structure, the calcarenite was tested both in the natural state and in the destructured-reconstituted state using both oedometer apparatuses and a high-pressure triaxial apparatus for isotropic compression (up to 10 MPa). Previous investigations of the destructuration of weak sandstones, e.g., [12,14], have highlighted that while destructuration occurs in both shear and compression, possibly more occurs during compression. Oedometer tests are of particular value since they apply a combination of volumetric and shear strains while large stresses and hence greater degrees of destructuration are more easily achieved. The use of compression tests is also more convenient in that the data show a continuous evolution of the destructuration with increasing stress, which could only be achieved by multiple shear tests. It has to be noted that oedometer tests are commonly and widely used for fine soils rather than for weak rocks. Hence, by adapting this test to the research purposes, high stresses have been reached by means of a high-pressure apparatus (up to 270 MPa), in addition to a standard apparatus (up to 24 MPa) with a conventional 38 mm diameter fixed ring oedometer. The oedometer tests were complemented by isotropic compression tests, which allow an investigation of destructuration in two forms of compression, one with solely volumetric strains and one with a combination of volumetric and shear strains. As for the high-pressure apparatus in one-dimensional conditions, the vertical load was applied to the soil sample located inside a steel ring (diameter 40 mm and height 22 mm). The load was applied by using a mechanical loading frame of 490 kN, the displacement was set at a constant rate of 0.033 mm/min. In order to minimise side friction effects—no floating rings were available—silicon grease was lightly spread over the inner surface of the ring. As for the computer-controlled triaxial tests, isotropic compressions were carried out by means of a stress path apparatus which was supplied and built by the technicians of the Imperial College of London and can reach stresses up to 10 MPa. A 50 kN capacity submersible load cell and 100 bar Keller pressure transducers were used to measure the axial load during shearing and cell pressures, respectively. During testing, water-submersible linearly variable differential transformers (LVDTs) were measuring local axial and radial strain values. Measurements of volume change were obtained by means of a volume gauge. Triaxial test samples have standard dimensions (38 mm of diameter and 76 mm of height), as shown in Figure 2.

Figure 2. Triaxial test natural sample (D = 38 mm, H = 76 mm).

A Skempton coefficient B higher than 0.97 was always achieved so that a full saturation was always assured. High stresses were reached in order to pass the yield stresses in compression. The destructuration of materials where the cement and particles have strengths that are broadly similar is problematic, particularly when the cement invades the macro inter-pore space as in Figure 1. Two methods were therefore used, which were as gentle as could be used, whilst breaking down the structure. The first method of destructuration consisted in applying freezing and thawing cycles while the second method was carried out through the application by hands of compression forces between the grains by tamping and gentle hammering. Reconstituted samples were gently achieved by compaction through a 1 kg pestle. Tables 1 and 2 summarise details (initial dry unit weight γ_{d0}, initial specific volume v_0, higher stress level reached during the test σ'_v, method of reconstitution) of all the tests carried out in the oedometer apparatuses and in the triaxial cell, respectively.

Table 1. Details of the oedometer tests (ON Natural, OD Destructured).

Test	γ_{d0} [kN/m^3]	v_0	σ'_v [MPa]	Method of Reconstitution
ON1	13.08	2.05	210	
ON2	13.55	1.98	210	
ON3	13.50	1.99	203	
ON4	12.45	2.16	24	
OD5	13.79	1.95	270	Tamping/hammering
OD6	14.51	1.85	270	Tamping/hammering
OD7	15.19	1.77	250	Freeze/thaw
OD8	15.82	1.70	250	Freeze/thaw
OD9	13.37	2.01	24	Tamping/hammering

Table 2. Details of the isotropic compression tests (ISO-N Natural, ISO-D Destructured).

Test	γ_{d0} [kN/m^3]	v_0	σ'_v [MPa]	Method of Reconstitution
ISO_N1	13.44	2.00	10	
ISO_N2	13.69	1.96	8	
ISO_N3	12.43	2.16	7.5	
ISO_N4	12.70	2.12	6.5	Loading and unloading cycles
ISO_D1	13.66	1.97	10	Tamping/hammering

3. Results and Discussion

In Figure 3, it is possible to observe compression test results (1D and isotropic). A discussion on the compression behaviour together with breakage data will be presented in this section for natural and destructured specimens.

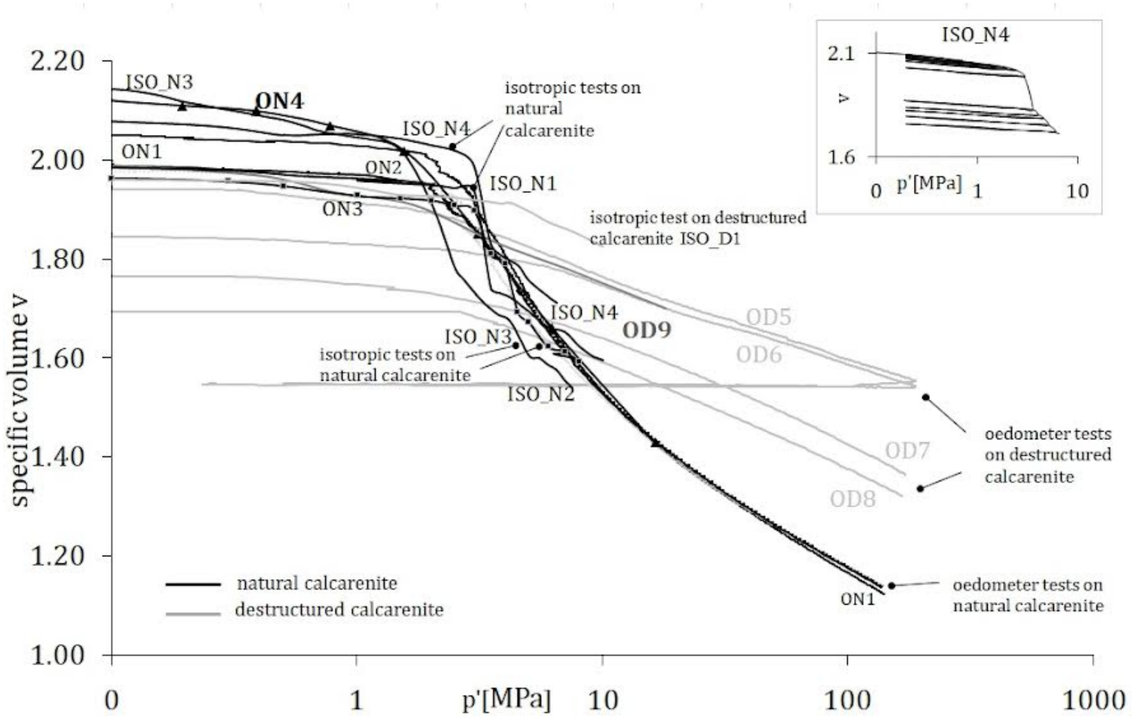

Figure 3. Isotropic and 1-D compression curves for natural and destructured samples of lithotype B2.

3.1. Compression Behaviour

Starting from a similar initial void ratio, in order to highlight the effects of structure, compression lines of the calcarenite samples at the natural state and after destructuration were drawn and compared. As expected, natural samples point to the typical gross yield behaviour while compression curves with very mild curvature and no abrupt drop at any stress feature the destructured specimen compression behaviour. Higher stiffness at higher stresses can be observed in the destructured sample compressive behaviour all through the loading process. Despite the mineralogy, which is similar for natural and destructured samples, no unique 1D- NCL can be recognised at high stresses. This behaviour is evidence of distinct final fabrics. Tests OD9 and ON4 were carried out in a different oedometer apparatus by loading samples obtained from the same block, up to lower stresses (24 MPa), but they confirm the behaviour of natural samples (ON4) and destructured ones (OD9), respectively. These two tests were carried out to confirm the behaviour and exclude any possible effect of the type of apparatus.

While the compression paths of the intact samples seem to curve as they approach v = 1 the reconstituted samples do not show such tendency and maintain much higher specific volumes, which must reflect a rather different arrangement of particles and voids. The compression behaviour of the destructured specimens is therefore characterised by curves that lie on the right of the natural soil curves, no matter the method used to achieve destructuration (i.e., tamping and hammering or the less disturbing procedure of freezing and thawing cycles). It is also noticeable that the compression curves of the reconstituted samples do not tend towards a unique NCL. This unexpected behaviour makes it no longer possible to consider the destructured calcarenite as a reference material, as has been the case for other weak rocks, e.g., [12,20]. Hence, it is important to highlight that in this research work, terms such as "destructured" or "destructuration" are conventionally adopted even if this material cannot be considered as a reference material.

A direct comparison between oedometer compression and isotropic compression curves is shown in Figure 3. A value of K_0 (i.e., coefficient of earth pressure at rest) equal to 0.5 was assumed in order to compare compression paths in the *v* vs. *log p′* plane. This value may result in overestimation for the cemented natural samples [12]; however, a change in its estimation does not influence the shape of the curve significantly because of the *log* p' scale and because a change of K_0 only shifts the compression curve in this plane. The conclusion on the higher stiffness of the destructured samples will be not affected by this. As for the isotropic compression curves, the typical gross yield can be recognised in all natural samples [19], while very mild curvature and no abrupt yield can be seen for the compression path of the one and only specimen that was destructured by tamping and hammering, ISO_D1. It seems that the initial state (natural or destructured) controls the compression behaviour. This can be confirmed by observing the test ISO_N4 which behaves like natural samples even if the structure was modified (i.e., destructured) by means of loading and unloading paths during the test. Hence, the destructuration process carried out by the other method (tamping and gentle hammering) before the test during sample preparation before is a completely different phenomenon if compared to the destructuration occurring during natural sample compression in the triaxial cell. Data have then been compared to the oedometer test curves.

Even if there is uncertainty in the value of K_0, the data from the one-dimensional and isotropic tests on natural samples seem to match accordingly. To confirm results, two further oedometer tests were carried out (ON4 and OD9) for which structure analyses were carried out by means of tomography investigation. From the direct comparison of the two tests, it was possible to observe much higher strains achieved for the natural soil compared to the destructured one. The destructuration process carried out to create the reconstituted samples cannot be considered a weakening process. A new structure with its own mechanical features (i.e., higher stiffnesses in compression) is induced by destructuring the material to prepare samples.

3.2. Grain Crushing

In Figure 4a, grading curves are shown before and after oedometer tests. Final particle size distributions were determined at the end of tests for both kinds of samples (destructured and natural). Initial gradings were only determined for those samples that have been destructured before testing. For cemented (i.e., natural) samples the initial grading is unknown and defining what is cement and what is particle is ambiguous for cases where the cement part fills the pore space. Nevertheless, it is instructive to compare the final gradings of natural samples with the initial gradings of samples destructured by tamping and hammering. This shows that similar gradings are achieved by compression and destructuration by tamping and hammering.

However, in Figure 4b, comparing the initial gradings of samples destructured by tamping and hammering (OD5 and OD9) and samples destructured by means of several freezing and thawing cycles (OD7), it is clear that freeze/thaw actually produces more fines, which was unexpected as it might have been thought to be the gentler method. The greater fines content may be the reason why the freeze/thaw samples tend to be initially a bit denser than those produced by tamping and hammering.

Figure 4c isolates the effect of stress level for the destructured samples also showing values of relative breakage Br [21]. Within the scatter that occurs in such heterogeneous materials, there would appear to be no evident influence of the destructuration method but only of the vertical stress. Comparing the final gradings of the natural samples with those of the destructured ones in Figure 4d, large amounts of fines seem not to be created in the natural samples despite the extremely high vertical stresses reached.

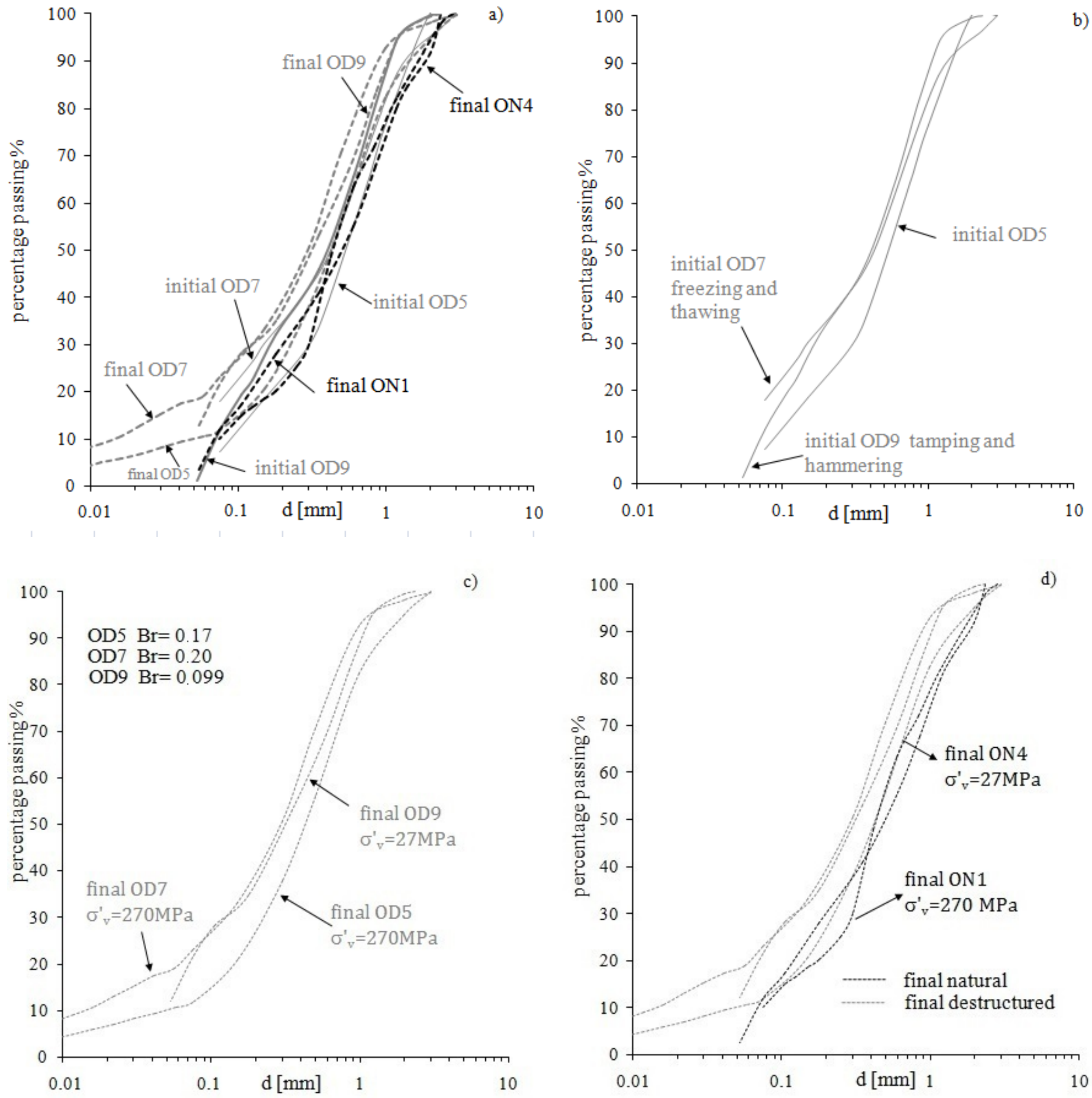

Figure 4. Particle size distributions (PSD) in oedometer tests. (**a**) Initial and Final PSD; (**b**) Initial PSD for destructured samples with different methods; (**c**) Influence of stress level on final PSD for destructured samples and relative breakage Br; (**d**) Final PSD for natural and destructured samples.

In uncemented sands, Yan and Shi [22] showed that if samples are subjected to cycles of high pressures in compression, reconstituting between each cycle, the soil tends to become denser as it becomes well-graded and the compression curves become flatter, but they tend to converge to that of the original soil at high stress levels. This is quite different from what is seen here, where the initial density is little affected and the compression curves are very different, crossing at relatively modest stresses. This indicates that the effects of destructuration of such soil by compression or remoulding are more complex than simply an effect of particle breakage.

3.3. Analysis of Structure

The tomography data (Figure 5) were obtained for two samples tested at the same pressure in the oedometer apparatus (ON4 and OD9). Same boundary conditions are necessary to highlight differences between the initial natural and destructured samples (ON4 and OD9, respectively). Results illustrate the different fabrics obtained at the end of the tests at 24 MPa. The comparison indicates a more dispersive fabric for the destructured sample if compared to the image of the natural one. From a comparison between the images of thin sections (see small boxes in Figure 5) at the end of oedometer tests between a natural sample and a destructured sample, it was possible to observe the presence of a smaller amount of macropores in the natural specimen.

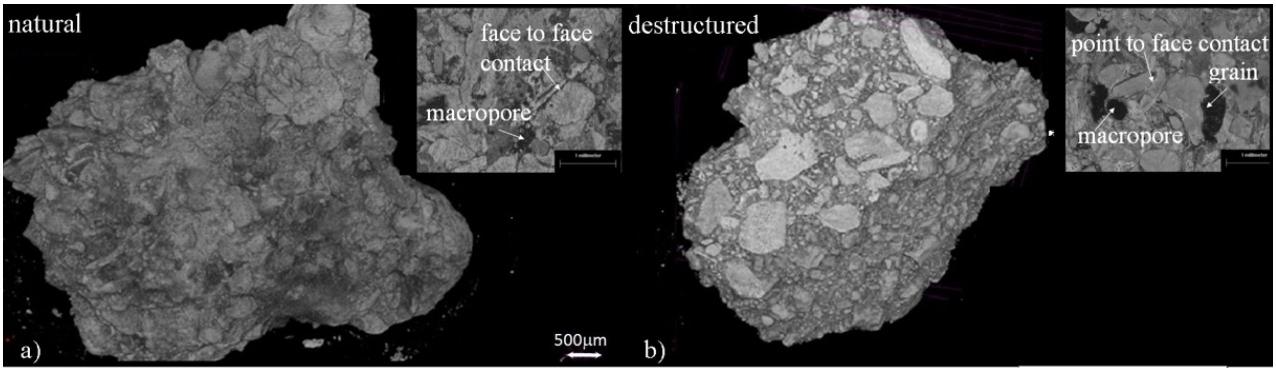

Figure 5. Micro-CT images from the Bruker Skyscan: (**a**) after oedometer test ON4; (**b**) after oedometer test OD9.

It can be hypothesised that the presence of more face-to-face contacts between grains in the natural samples and more point-to-face contacts between particles in the destructured ones may be the cause for and/or the effect of the different fabrics. It is possible that the presence of a meso-structure in the destructured sample, which results in being hard to be modified even if high stresses are reached, causes the differences in behaviour. The porosity data from the CT scanning in Table 3 on small portions of specimens confirm that natural samples reach a much lower value of porosity at the same stress level. The closed porosity of the natural sample would imply an error in the specific volumes of only about 0.02 if all the closed voids were water-filled. However, this is most unlikely given the sampling environment and in any case, this would be an upper bound since the CT scan was on a larger, more intact fragment and most of the sample was even more destructured.

Table 3. Data from Micro-CT (Bruker Skyscan) after test.

Test	Total Porosity	Closed Porosity
ON4	4.27%	3.01%
OD9	14.79%	0.50%

4. Conclusions

The compression behaviour of natural and destructured samples of the Marsala calcarenite shows that the destructuration cannot be considered necessarily a procedure that causes a "decay" of the mechanical features (i.e., weakening). It seems instead a process that forms a new structure (i.e., fabric) and a dissimilar mechanical behaviour. The initial structure can be considered as an internal state variable. Together with the specific volume, both can be responsible for controlling the mechanical behaviour. For a material of this type, where cement bonds and particles are difficult to distinguish and the macro-pores are part cement-filled, it is possible that the intact soil is less stiff than the destructured one and that destructuring, even when carried out as gently as possible, may not provide a suitable reference material. The destructuration seems to produce forms of fabric that are difficult to erase and are not representative of the intact soil and hence a "negative" effect of structure can be seen. For the destructured material, higher porosities are reached so that, despite more fines being present, a more dispersive fabric compared to the natural can be highlighted.

Such terms as particle or bonding need to be revised in a material in which it is hard to distinguish bond breakage and particle breakage. Further study, perhaps by means of mercury intrusion porosimitery (MIP) or more detailed CT scanning may reveal how voids and macro-pores participate in the loading processes of these materials and determine what are the fundamental mechanisms that cause the differences in compressibility between the natural and destructured calcarenite. Therefore, as a suggestion for further research, the influence of stress history need to be investigated in order to assess its role in causing different structure (i.e., fabric) and such a behaviour together with the presence of a multiplicity of contact modes.

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