The Effects of Structure on the One Dimensional Compression Behaviour of a Porous Calcarenite

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Abstract. Human settlements built on weak rock deposits are often characterized by instabilities or collapse that may involve the underground cavities and consequently the above buildings. Underground calcarenite quarries in Marsala have been involved in a number of collapses that have seriously damaged numerous buildings. Unfortunately proper engineering solutions have not yet been identified according to the different and special cases and to the properties of this structured material. In order to investigate structure effects on the behaviour of the porous calcarenite of Marsala, this paper presents a comparison between the one dimensional compression behaviour of the intact rock and of the same weak rock in the reconstituted state. The investigated lithotype is a metastable rock whose mechanical behaviour is strongly affected by its structure, which is commonly distinguished in the literature as a combination of fabric and bonding. The investigation has highlighted original results, not reported in the literature for this material, such as the irrelevance of bonding in determining the stiffness. A laboratory study was also undertaken to assess the use of polymer treatment or inorganic consolidants as a solution to improve the mechanical behaviour of this weak rock.

Keywords: Structured soil · Yielding behaviour · Underground quarries · Stabilizer treatment

1 Introduction

In the Mediterranean area, in towns like Malta, Palermo, Ragusa and Marsala, human settlements built on weak rock deposits are often characterized by the presence of open pit excavations and, frequently, by underground quarries. As a consequence of urban expansion, quarries of exceedingly large extension made of pillars of poor mechanical

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properties were formed, causing conditions of instability. The structured quaternary rocks outcropping in Marsala, belong to the calcarenitic-sandy-silty complex.

In the past, the scientific literature has investigated the definition of a framework for structured soils. The major developments of Critical State Soil Mechanics have defined the mechanics of natural clays and the influence of their structure (e.g. Cotecchia and Chandler 2000). As suggested by Burland (1990), the effect of soil structure on the mechanical behaviour of a natural soil can be assessed by comparing its mechanical properties in the intact state to its mechanical properties in its remoulded or reconstituted state at the same void ratio. The void ratio at a given p' of a structured soil can be expressed by the following equation: $e = e^* + \Delta e$, where Δe is the difference in void ratio between a structured soil and its corresponding reconstituted soil at the same p'. It usually has a positive value (i.e. effect of structure). However, negative values of Δe have also been reported for some structured natural clayey soils which are featured by intensive fissuring (e.g. Fearon and Coop 2002; Vitone and Cotecchia 2011), for these soils the mesostructure represents an internal state variable in addition to specific volume in controlling the mechanical response so that the material is less compressible than the reconstituted clay.

The results on some natural calcarenites and artificially cemented calcarenite (Lagioia and Nova 1995) show that the Normal Compression Lines NCLs of structured and reconstituted soils can be seen within a critical state framework where compression paths converge to a single intrinsic line despite the material being a bonding or a fabric-dominated sand. When the structure is characterized by strong particles and weak bonds, the compression lines of cemented and uncemented soils run parallel even at very high pressures (e.g. Rios et al. 2012). Despite that, no negative effective of structure for sandy soils, either cemented or not, has been observed in any of these cases, as observed for the intensively fissured clays (e.g. Fearon and Coop 2002; Vitone and Cotecchia 2011).

The present research shows test results on intact and reconstituted samples of calcarenite that were carried out to characterize the mechanical behaviour of the lithotype B2, identified in previous studies (e.g. Zimbardo et al. 2018). Moreover, with the aim of identifying an effective treatment able to improve the stability of these areas, an investigation was carried out on the structured material with different percentages of polymers and nanolime, which penetrate, consolidate and strengthen the material, as suggested by many researchers on the field (e.g. Taglieri et al. 2018). Nanolimes are aimed at overcoming some of the limitations of traditional lime-based materials, such as the reduced penetration depth and the difficulty in achieving a complete carbonation, while maintaining their advantages (e.g. Daniele et al. 2008) and with fewer side effects (e.g. Dei and Salvadori 2006).

2 Materials and Methods

The calcarenite of Marsala is a heterogeneous weak rock the strength and deformability of which are related to its geological and structural features (e.g. Zimbardo et al. 2015). Among the lithotypes identified, in this note, only investigations on lithotype B2 (Fig. 1), which constitutes the majority of the skeleton of the quarries, are presented.

According to the ISRM, lithotype B2 is classified as EM, rock of low strength (class E) and of medium deformability (M).

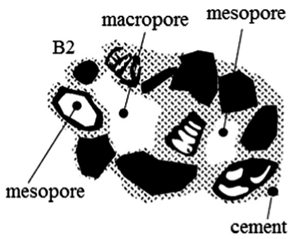

Fig. 1. Representation of lithotype B2

The mechanical behaviour of lithotype B2 was investigated by means of oedometer tests and isotropic compression tests carried out on specimens, in the natural and destructured initial state, obtained from cube block samples sampled in situ. As for the soil classification, a value of 2.74 for the specific gravity Gs, measured by means of a thermo helium pycnometer, was detected. The average value of the dry unit weight γ_d, is equal to 14.11 kN/m^3, the porosity is on average 51% while the final saturation degree is between 75% and 97%. Previous research on this lithotype (Zimbardo 2016) highlighted the presence of a strong bonding. Thin sections were observed by means of a petrographic microscope. As regards composition, the grains are mainly bioclasts (96.4%) while lithoclasts are rare, so the rock is more appropriately referred to as a biocalcarenite. The shape and the size of the clasts (100 μm up to 8 mm) vary greatly and no preferential orientation of grains can be highlighted.

The effects on inter-particles bonding were investigated by comparing the stress-strain behaviour of the natural specimens to the destructured soils for which the destructuration was produced by several freezing and thawing cycles or by the manual application of compression forces between the grains (by tamping and hammering). The compaction of reconstituted samples was carried out by means of a pestle of 1 kg. In order to reach the yield stresses and to observe the natural destructuration afterwards, very high vertical effective stresses (σ'_v) were reached in the oedometer tests (i.e. 270 MPa). In isotropic compression, lower values of the mean effective stress (p') were reached (up to 10 MPa).

For the treated samples, specimens cut from the same block were put into a ceramic vessel and totally submerged, for 20 days, with the stabilizer mixture of Polyethylene glycol (PEG) and nanolime in different proportions by weight. In the present study the product "CaLoSiL IP25" by "IBZ-Salzchemie Gmbh & Co.KG" (25 gr/l di Ca(OH)2) for deeper penetration was used, a suspension of colloidal nano-sized particles of calcium hydroxide (Ca(OH)2) in isopropanol. The PEG600 used is a PEG by Sigma Aldrich, which seems to be a good stabilizer for collapsible soils (Zimbardo et al. 2019), is a liquid with a viscosity 150–190 mPa s at 20 °C.

Specimens were weighed, removing the excess of liquid from the surface, at intervals of time, measuring the percentage of the ratio Vs (stabilizer volume/total volume) in order to evaluate the mixture absorption. It was observed that Vs increased rapidly during the first day of soaking. Once, the samples had reached a more or less constant Vs, they were dried 20 days in atmospheric condition. As a preliminary study, three oedometer tests were carried out up to a vertical effective stress of 14 MPa on the treated material mixed as follows: (1) 50% nanolime and 50% PEG, (2) 70% nanolime and 30% PEG, (3) 100% nanolime. The percentages are defined by weight.

3 Results

The results of oedometer tests conducted are shown in Fig. 2. A direct comparison between the compression paths of the natural samples of the calcarenite and the destructured ones, at similar values of initial void ratios, highlights the structure influence. As observable, the natural structured samples showed the typical gross yield state while the destructured specimens follow compression paths with very mild curvature, with no abrupt drop in stiffness at any pressure. The destructured specimens show higher stiffness and a behaviour which is compressive all through the loading process and, despite the identical mineralogy of the structured samples, no common 1D- NCL line is eventually reached at high pressures, highlighting the presence of different final fabrics. The resulting fabric, at the end of the compression paths, seems to highlight a new arrangement of particles which is featured by a higher value of the specific volume with no possibility of reaching the lowest possible value of $v = 1$ which seems to characterize the compression paths of the natural samples. Hence, in this paper, the conventional terms “destructured” or “destructuration” are used even if the material in this state cannot be considered, as seen in the literature, as a reference material. Summarising, the mechanical behaviour is characterized by the compression curves of the destructured samples all located on the right of the structured material at high stresses after the yield stress, no matter whether the destructuration process was obtained by tamping and hammering or by a less disturbing procedure such as after freezing and thawing cycles.

A direct comparison of the oedometer compression paths with the isotropic compression paths is shown on Fig. 3.

In order to compare stress path on the v, ln p′ plane, a value of the coefficient at rest, $K_0 = 0.5$ was assumed even if this value may be rather overestimated for cemented natural samples. It is possible to observe that isotropic compression paths of the natural samples (ISO_N1, ISO_N2, ISO_N3, ISO_N4) show the typical gross yield state while the destructured specimen ISO_D1, destructured by tamping and hammering, follows a compression path with very mild curvature, with about no abrupt drop in void ratio. The initial state (natural or destructured) seems to rule the behaviour, as can confirmed by observing ISO_N4 which, even if it was destructured during the test by means of loading and unloading cycles, still behaves as the other natural samples, proving that the destructuration process by tamping and hammering (see test ISO_D1) is a completely different phenomenon than the destructuration that occurs during the compression on natural samples (ISO_N1, ISO_N2, ISO_N3, ISO_N4). Despite the uncertainty on the value of K_0, data of the oedometer and isotropic tests on natural samples seem to agree.

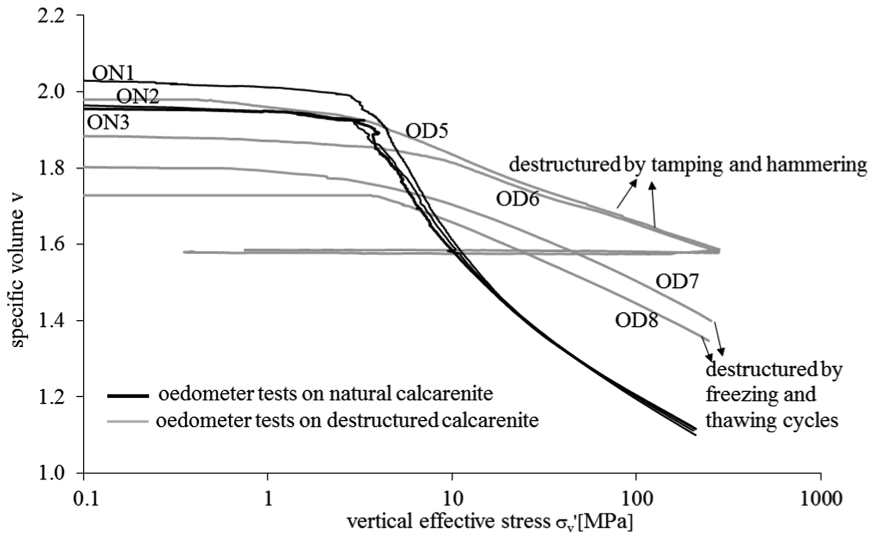

Fig. 2. Oedometer compression paths for structured and destructured samples of lithotype B2 of Marsala Calcarenite

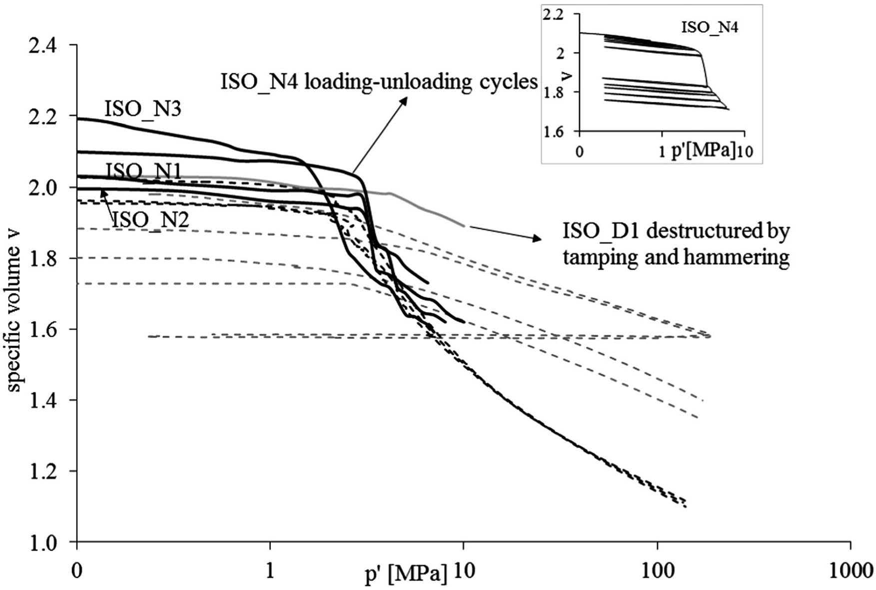

Fig. 3. Isotropic and Oedometer compression paths for structured and de-structured samples of lithotype B2 of Marsala Calcarenite

Hence, the natural soil is characterized by higher deformations if compared to the destructured one. The destructuration process used to create the destructured samples on this lithotype of calcarenite cannot be considered as a weakening process, but rather a process which determines a new fabric with its own mechanical characteristics, with higher stiffness.

In Fig. 4a particle size distributions before and after oedometer tests are shown. Looking at the initial particle size distributions of the destructured samples (i.e. OD5; OD7), it is possible to observe that even if the stress level applied was similar, the destructuration (see initial particle size distribution) obtained by tamping and hammering (i.e. OD5) is less than that obtained by the particle crushing (or bonding breakage?) in the sample that was destructured by several freezing and thawing cycles (OD7) which corresponds, then, to a different fabric. Looking at the final distributions, after the oedometer tests, despite the high vertical stress reached during the test, large amounts of crushing are not occurring. For the natural sample subjected to oedometer compression (ON1), even if no initial distribution could be determined, the final grading is close to the "destructured" distributions showing that the destructuration process during the test leads to a similar particle size distribution obtained before the test by tamping and hammering. Therefore, comparing the final distributions for samples OD5 and ON1, no difference can be observed in terms of size distributions and, according to Fig. 2, if a certain amount of particles or bonding has been destroyed in both cases, different fabrics must have been obtained, leading to the hypothesis that macropores are still present in the fabric of the destructured samples. In Fig. 4b, where final particle size distributions for the natural samples are shown after the oedometer and isotropic compression tests, it is possible to observe that similar particle size distributions are obtained after isotropic compression and that particle crushing is slightly increasing after the oedometer tests (i.e. higher stress levels). It is possible to conclude that these grading analyses alone cannot help in identifying the new fabric. Measurements of pore distributions (i.e. porosimetry) are needed for the interpretation. Therefore, it is not so clear what is particle and what is bonding. Nevertheless, some comments can be made observing the thin sections of samples after tests. In Fig. 5, two photos of thin sections are shown, one for the natural and one for the destructured sample at the end of the tests.

Qualitatively it is possible to observe the presence of a higher amount of macropores in the destructured material (right) if compared to the natural (left). It can be hypothesized that the presence of different contacts can be the reason and/or the effect of the different obtained fabric, a meso-structure which is difficult to erase even at high stresses.

In order to investigate the effects of adding nanolime to the evolution of soil pore structures, the treated samples were analysed by means of an optical microscopy (Fig. 6). The images of the sample, stabilized with the mixture of 70% nanolime plus 30% PEG, revealed grains bonded within a calcium carbonate matrix.

The influence of the stabilizer mixtures is noticeable on the compression curve in Fig. 6 where the stress-strain relationships are compared with the untreated calcarenite (O1N). For stresses below the yielding pressure, the response in the oedometer test is stiff. After yield, for the stress levels reached, the treated curves shift parallel with the increment of nanolime content having higher post-yield specific volume. This is due to the carbonation process, responsible of the formation of the new calcite network between the original grains. It is evident the effect of nanolime on the compressibility

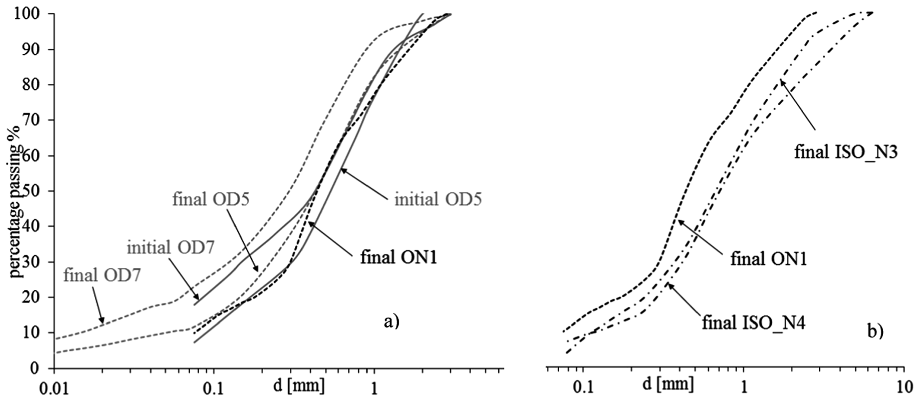

Fig. 4. Particle size distributions. (a) Comparison among oedometer tests (b) Comparison among natural samples

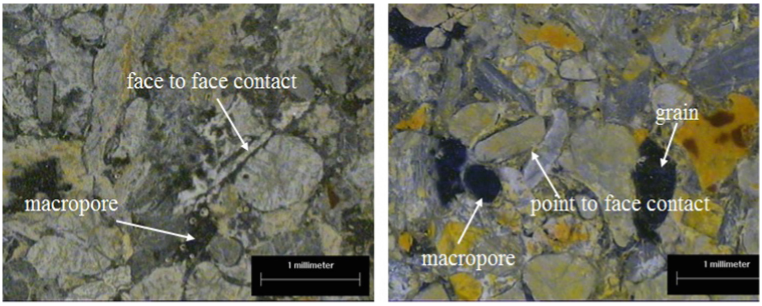

Fig. 5. Thin sections of natural (left) and destructured (right) samples at the end of the oedometer tests

of the calcarenite, in particular the treatment with 70% of nanolime and 30% of PEG seems to be more effective. This, indeed, seems to be the best combination among those tested; with more PEG (50%), nanolime has a reduced effect in increasing the stiffness and the yield stress, with less PEG (0%), the nanolime migration back to the surface, seen in visual inspection after a certain time of drying (20 days), will not assure a proper homogeneous distribution of the nanolime inside the specimen.

4 Conclusions

Oedometer tests and isotropic compression tests have been carried on the most common calcarenite of Marsala, lithotype B2, in order to characterize the material and to test the use of mixtures of polymer treatment and inorganic consolidant to find the most suitable solution to improve the mechanical behaviour of this weak rock.

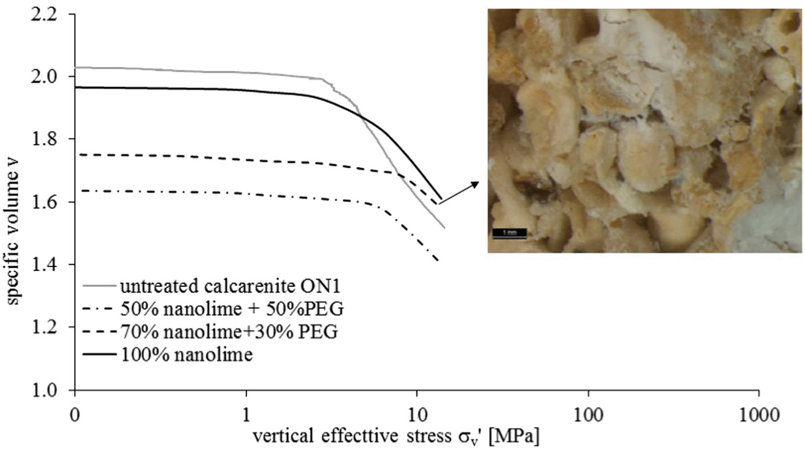

Fig. 6. Oedometer tests of treated materials and an image from optical microscopy

Conclusions and questions arising are reported as follows:

- For the studied calcarenite the destructuration is not a process of "decay" or "weakening" of the mechanical properties, but a process that determines new and different mechanical behaviours. The indelible mesostructure can be seen as an internal state variable in addition to specific volume in controlling the mechanical response so that the natural material is more compressible than the destructured material which cannot be seen as a reference material.
- The "destructured" soil reaches a new fabric. But how do voids and macropores take part in this process? What is the fundamental mechanism that causes the difference in compressibility between natural calcarenite and destructured calcarenite? Can have the stress history a role in determining this behaviour? Can be the presence of different type of contacts the reason or the effect of the different obtained fabric? These are questions that will need further research to address.
- Also not so clear what is particle and what is bonding. For this material do these terms have meaning, in a model where you distinguish bond breakage and then particle breakage?
- In the literature, nanoparticles of $Ca(OH)_2$ are considered as one of the best stabilizers for the conservation of calcareous substrates. According to the results on the lithotype B2, nanolime at 70% plus 30% of PEG appears to be the best stabilizing treatment among those tested. This preliminary achievement requires further study in order to assess on the long term efficacy and for in situ investigation.

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