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On The Compression Behaviour of Unsaturated Silty Tailings: An Experimental Investigation

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Abstract *- A detailed characterization of tailings under unsaturated conditions is essential to reproduce their stress-strain response and represents a key tool for assessing reliable stability analysis of tailing dams both during the design phase, the mining activities, and after operations cease. Given these aspects, this research shows the main results of an experimental campaign carried out on quarzitic tailings to analyse their hydro-mechanical behaviour under unsaturated conditions. The investigation consists of oedometer compression tests on the silty fraction of Stava tailings under constant water content conditions. The effects of the matric suction and sample preparation technique on the 1d-Normal Compression Line (1d-NCL), the compressibility, and the occurrence of a transitional behaviour are studied, with the suction level evaluated based on the water retention tests (WRC). The experimental results are compared with those obtained under saturated conditions and with literature data dealing with fine soils in an unsaturated state. The Basic Barcelona Model (BBM) was proved to successfully describe the dependency of the soil compressibility, the pre-consolidation stress, and the recompression also of tailing materials on their suction level.*

Keywords: Tailings, unsaturated soils, 1d-NCL, compressibility, pre-consolidation stress, Water Retention Curve

1. Introduction

Tailings storage facilities (TSF) are geotechnical structures used to store water and wastes that come as by-products from mining activities. Mechanical and chemical processes are used to grind up rock into fine sand to extract valuable minerals or metals from the patent ore. All the uneconomic and unrecoverable remnants from this process are waste, also known as 'tailings' and include water, finely ground rock particles, and chemical minerals. Depending on the extraction process used, tailings can be liquid, solid, or a slurry of fine particles. TSFs consist of a step-raised earth/rock embankment and a basin. A high permeability portion made of coarse sediments is usually placed close to the discharge point/dam, a lower permeability zone made of fine particles would exist far from the dam, and between them, there is a 'beach' with an intermediate permeability. The position of the water table within the basin is governed by several external factors due to the interactions with the atmosphere, resulting in a large portion of tailings in unsaturated conditions.

Owing to the complexity, a comprehensive characterization of tailings under unsaturated conditions is an essential tool for assessing reliable stability analysis ([1-4]). Guaranteeing the stability of tailing storage facilities represent one of the most challenging tasks in mining engineering. Indeed, these basins are vulnerable to collapse for the following reasons: i) dams are made of locally derived filling material such as tailings, soil, overburden material from mining operations; ii) dams are raised over time as

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solid material with a relevant increase in effluent, i.e. plus runoff from precipitation; iii) there is a lack of regulations on specific design criteria; iv) their large surface makes criticality identification difficult, and would require a continuous/extensive monitoring, which is time consuming and expensive; v) the cost of remediation works after the closure of mining activities is high ([5]). Many tailing dams' failures are related to the static liquefaction phenomena triggered by intense rainfall or rapid snowmelt which represent one of the major causes of tailing dams' collapse (Fig.1).

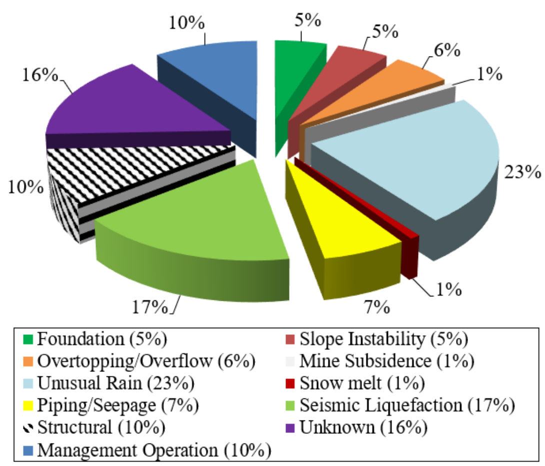

Figure 1. Distribution of the number of failures with respect to their causes in the world (modified from [5]).

Recently, safety problems have concerned many researchers studying tailings dams, as they have a high risk of failure due to static or dynamic liquefaction. Existing investigations of liquefaction in tailing wastes within a critical state framework have relied on the Critical State Line (CSL) being unique in the volumetric plane, but recent advances have highlighted a so-called "transitional" behaviour in which the location of the Normal Compression Line and CSL depends on the density of the soils at deposition. Indeed, some recent experimental studies have highlighted that many soils have a so-called "transitional" behaviour ([6-8]), in which samples of initially different void ratios show non-unique Normal Compression Lines in compression and non-unique Critical State Line in shear, so resulting in difficulty to characterize soil response under the critical state framework. Some researchers have shown that transitional behaviour can also be found in some types of tailings. Among them, [9] analysed data for Stava tailings and showed that silty tailings taken from different depths, but with similar grading did not have a unique Normal Compression Line. Despite this evidence, [10] performed oedometric tests on the same tailings, also with different gradings, and found no transitional behaviour. Recently, [11] carried out simple shear tests on gold tailings and observed a transitional behaviour, as well also [12] reported transitional behaviours in several other tailings.

There is also some debate about whether the initial fabric - resulting from different sample preparation methods - affects the soil response, as well as the liquefaction susceptibility. Experimental results obtained by [13] and [14] on Nevada and Toyoura sands showed that the undrained behaviours were influenced by different preparation techniques, giving temporary strain softening for moist tamped and dry deposited samples and strain hardening response for water pluviated samples. Similar results have been obtained by [15-16] and [17]. For tailings materials, the effect of the soil fabric on the mechanical response of gold tailings was investigated by [18] through scanning electron microscopy (SEM). They show that slurry deposition produced a uniform fabric and moist tamping created an aggregated fabric. They observed relevant differences in the soil response for the coarsest tailings but for the medium and finest sized tailings, the effect of sample preparation technique was negligible. On the other hand, many authors concluded that the sample preparation technique alone does not produce different structures that result in a non-convergence of the compression paths, and so they pointed out that the sample preparation method has no effects on the transitional behaviour of soils, among them [6-7] and [19-20].

In recent years researchers have been attempting to analyse unsaturated soil behaviour in terms of constitutive relations linking volume change, shear deformation, and strength in a single elastoplastic model. The Barcelona Basic Model (BBM) proposed by [21], is one of the most widely adopted elastoplastic critical state constitutive models for unsaturated soils. Representing an extension of the Modified Cam Clay Model, the BBM is intended to model low-moderate plasticity fine-grained soils and it can account for aspects of the mechanical behaviour of soils in unsaturated conditions in the (p, q, s) space by using matric suction and net stress as independent stress variables. Within the frame of BBM, the compression index decreases with suction. The model proposed by [22] is like BBM, but some simplifications are introduced to have a more flexible model. In Wheeler's model, the normal compression lines are fitted using experimental data at different suction, with an increase of the compressibility index with suction since large pores could occur during the drying process. Within the model proposed by [23], the behaviour of unsaturated soil is interpreted using the average soil skeleton stress (the difference between the total stress and the mean value of the fluid pressures weighted with the degree of saturation) as an effective stress. In the net mean stress-specific volume plane, the NCL is no longer linear and the compression index decreases with suction but increases with net stress always remaining smaller than the saturated compression index.

Within this context, the current research shows the results of an experimental campaign to investigate the mechanical response of quarzitic tailings collected after the Stava dam failure occurred in 1985. The mechanical behaviour under unsaturated and nearly saturated is studied by performing both oedometric and water retention tests. The effects of a wide suction range and the sample preparation technique on the compressibility/re-compressibility index, on the Normal Compression Line, and on the yield stress are investigated. The outcomes are interpreted using the Basic Barcelona Model and compared to those obtained under saturated conditions and with literature data on different soils or tailings.

2. Testing material

2.1 Geotechnical characterization

Tailings under investigation were collected from the lower portion of the upper dam after the Stava dam's collapse occurred in 1985 (Fig.2-3), leading to 268 fatalities, and environmental damages. A poor drainage, the high phreatic level, and the unconsolidated state of tailings were supposed to be the main factors that caused the static liquefaction, leading to the collapse of the Stava embankment ([4],[24]). The material investigated is the fraction passing through ASTM sieve n°200 since it represents the finer tailings fraction deposited into Stava basins. The grain size distribution is given in Fig.4 and the clay fraction is 8% of the total solid mass. The liquid, plastic limit, and plasticity index are w_L=27.4%, w_P=18.0%, PI=9.4% ([10],[25]). Hydraulic conductivity and specific gravity are k=10^{-7}m/s and GS=2.83, while quartz, calcite, and fluorite are the main mineral constituents.

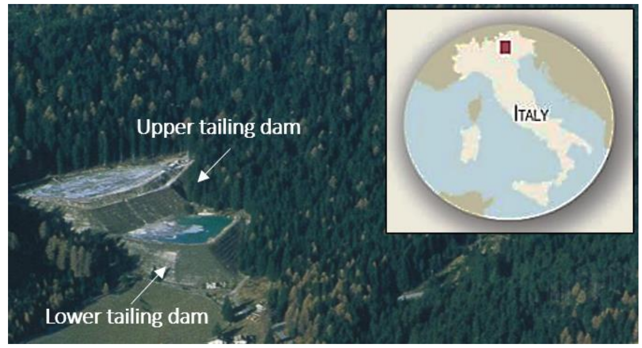

Figure 2. The Stava tailing dams before the collapse ([26]).


Figure 3. The Stava embankment after the failure ([26]).

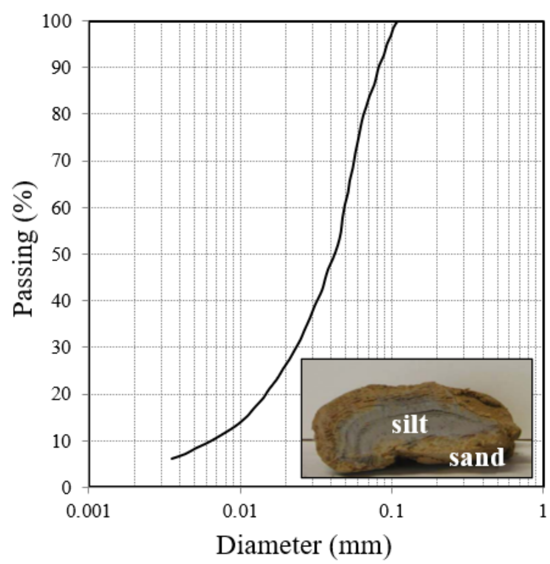

Figure 4. Grain size distribution of the silt fraction of the Stava tailings (modified from [10]).

Experimental studies performed by [27] and [28] allowed to estimate the shear strength properties of the silty fraction of Stava tailings, c=0kPa and φ_{cv}≈32° (Fig.5).

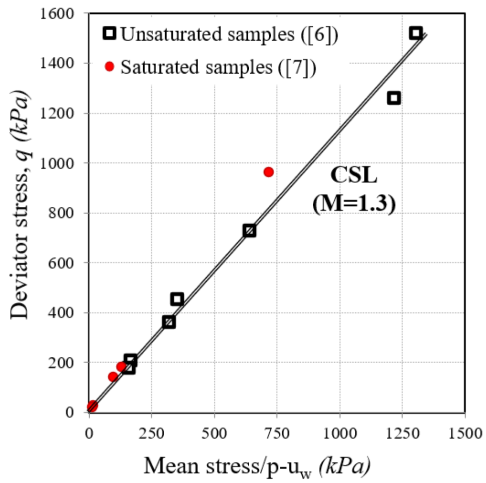

Figure 5. CSL for Stava silty tailings (modified from [27-28]).

2.2 Water retention response

Previous researches ([1],[29]) investigated the water retention response of the soil studied in the current research. The water retention properties of Stava silty tailings were found to depend void ratio. Such a dependency was interpreted through the WRC model proposed by [30] whose calibrated parameters are provided in [1]. The dependency of the main drying and main wetting branches on the void ratios of interest for the current research are given in Fig. 6 where loose samples clearly exhibit lower air entry values, and so a lower water retention capability.

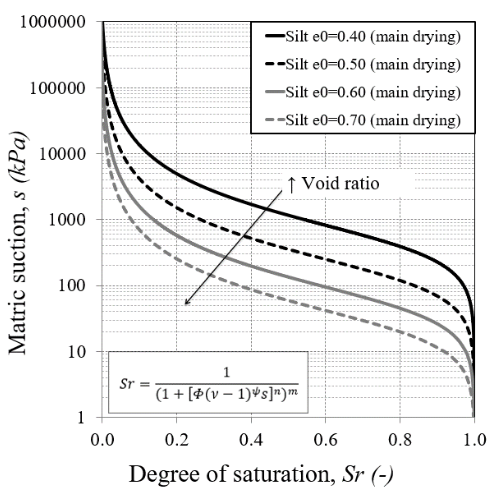

Figure 6. Influence of void ratio on the WRC of the silty fraction of Stava tailings (modified from [1] and [29]).

It is worth to note that the matric suction (s) is assumed to be the main component of the total suction (ψ) in non-plastic soils with a pure pore fluid, while osmotic suction is appreciable in high plastic clays or when the pore fluid contains dissolved salts. According to [28], Stava silty tailings are low plasticity-inorganic soils, so that the osmotic suction is a small amount of the total suction, therefore $\psi \approx s$.

3. Methodology

3.1 Sample preparation and experimental device

The experimental campaign was carried out at the soil testing laboratory of the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) on unsaturated samples (Sr≤90%) and nearly saturated samples (90%<Sr<100%) having d=50mm, h=20mm. Specimen were prepared by hand-mixing a certain amount of dry soil with the required amount of demineralized, de-aired water to obtain the desired initial water content ([31]). The mixture was then put into a hermetic cylindrical mold, and statically compacted (SC) by gradually applying an axial force until the desired volume was reached. During the assembling of the mold, two plexiglas plates were placed on the bottom and the top face of the sample to avoid the exchange of water, and grease was applied around the mold preventing water leakage. The oedometer tests were performed under constant water content conditions, so no water was placed into the reservoirs. Indeed, a mass-based analysis performed at the end of each test showed negligible variations of the water content during the entire compression test. An axial loading sequence was imposed at regular intervals (0.1MPa→12MPa), followed by an unloading path. The axial displacements experienced by the sample were detected by using an external linear variable differential transducer (full range 2.5mm; accuracy: ±2μm) allowing the void ratio to be evaluated at each step.

3.2 Previous experimental studies

Previous investigations ([28]) on silty Stava tailings were carried out by performing oedometer tests on statically compacted, fully saturated samples. More recently, [32] tested the same tailings in the form of slurry: the sample was prepared by imposing a known amount of soil and a water content equal to the liquid limit ('remolded sample'). A back-analysis performed at the end of the test allowed the estimation of the initial void ratio and degree of saturation (Sr=100%). Table 1 gives the initial state of the Stava silty samples tested in the current research, in [32] and in [28].

Table 1. The initial state of the Stava samples.

Sample	e_0 (-)	Sr (%)	Prep. Meth.	Comments
edo_0.517-093	0.510	93	SC	Current research
edo _0.593-091	0.593	91	SC	
edo _0.528-078	0.528	78	SC	
edo _0.568-074	0.568	74	SC	
edo _0.650-066	0.650	66	SC	
edo _0.520-0.28	0.520	28	SC	
edo _0.760-100	0.760	100	RS	[32]
edo _028	0.772	100	SC	[28]
edo _020	0.885	100	SC	
edo _019	0.925	100	SC	
edo _018	0.750	100	SC	
edo _017	0.930	100	SC	

4. Experimental results

As a preliminary effort, the suction level reached by each unsaturated sample during the compression tests is evaluated from its WRC (Fig.7). Indeed, knowledge of the water ratio e_w=Sr·e (which considers the combined effect of both the degree of saturation and void ratio) allowed to define a vertical hydraulic path because of the constant water content conditions imposed during the oedometric test. The hydraulic path crosses the WRC main wetting branches evaluated at the void ratio reached by the 1d-NCL, therefore the suction level is obtained as the average value. A suction level equal to 13kPa and 35kPa were estimated for unsaturated samples edo_0.528-078 and edo_0.650-078, respectively (Fig.7).

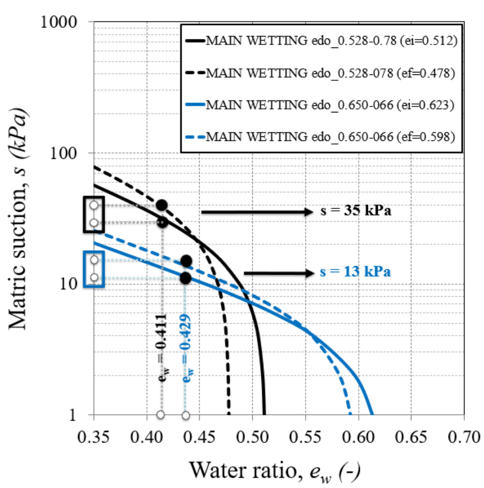

Figure 7. Samples edo_0.528-078 and edo_0.650-066: evaluation of matric suction level during compression test.

All the tests performed on the saturated samples are given in Fig.8: results obtained by [28] on SC samples are represented by black curves, while the red curve refers to the test performed by [32] on the RS sample. At high stresses 4-12MPa, the two sets of curves tend to converge toward a unique 1-d NCL regardless of the sample preparation technique: the compressibility index is estimated 0.104, leading to confirm the absence of a transitional behaviour. The term "transitional" is intended to refer of the behaviour of reconstituted/remoulded materials where the initial structure of the soil leads its compression or shearing response even at very high stresses and strains. It is important to notice that, according to [33], the term "structure" in soil mechanics is intended as a combination of the inter-particle forces ("bonding") and the particle arrangement ("fabric"). In this frame, transitional soils represent an example of the effect of the robustness of the initial structure, particularly the fabric, during compression and shearing. The uniqueness of the 1d NCL regardless of the preparation method of the fully saturated Stava tailings investigated in this research finds a good agreement with the experimental outcomes shown by [34] for some fine iron tailing specimens prepared through different initial densities and different methods, i.e. slurry, wet or wet compaction (Fig.9). Also in that case, the curves converge toward a unique 1-d NCL at stress range between 2MPa and 10MPa. If tests performed on SC nearly saturated samples (green lines) are plotted in the compression plane together with SC fully saturated samples (black lines), a certain transitional behaviour can be observed (Fig.10) at high stresses (4-12MPa).

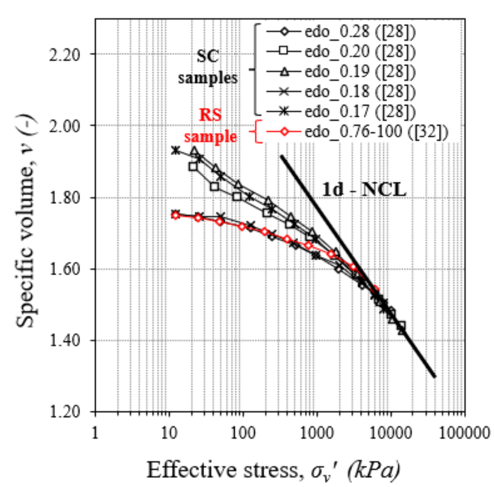

Figure 8. Stava tailings: effect of the preparation method.

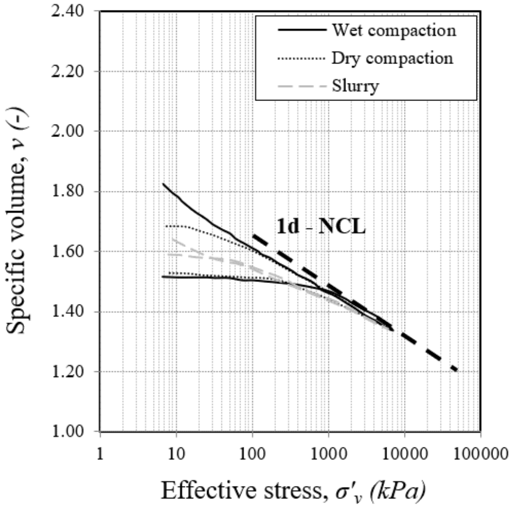

Figure 9. Literature data: effect of the preparation technique on saturated samples. ([34]).

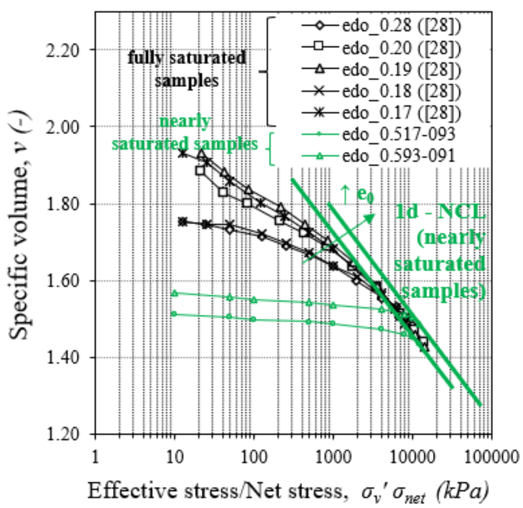

Figure 10. Stava tailings: effect of the initial density on the mechanical response of nearly saturated SC sample.

This preliminary experimental evidence suggests that, for Stava tailings, the void ratio affects the mechanical response of the soil in terms of transitional behaviour when the saturation state is lower than the unit. Further investigations in this direction, could deal with unsaturated samples having larger differences in the initial void ratio, but paying attention to avoid any segregation of the soil at water content that are too high. According to [21], an increase of the compressibility index can be observed as the matric suction decreases, as shown by the slope of the 1d-NCL given in Fig.11 for a suction range between 13kPa and 700kPa. The suction levels corresponding to the different curves, estimated by the water retention curves, are due to the combined effect of the void ratio and water content of the samples during the oedometric compression. If just the effects of the saturation on the soil compressibility are analysed, samples edo_0.528-078 (red line) and edo_0.520-028 (purple line) can be considered. Indeed, they have a similar initial void ratio (e_0=0.52), but different initial water content (or degree of saturation): the compression index decreases from λ=0.059 to λ=0.049 when the water content turns from w(s:13kPa)=15% to w(s:700kPa)=5%. The variation of the compression index is supposed to be due to the relevant increase of the soil stiffness with the water content reduction. On the other hand, if mainly the effects of the density on the soil compressibility are investigated, samples edo_0.528-078 (red line) and edo_0.568-074 (blue line) should be observed since they have quite similar initial water content (w_0=14-15%), but different initial void ratio: the compression index increases from λ=0.052 to λ=0.055 when the initial void ratio turns from e_0=0.53 to e_0=0.57. In this case, the compression index variation is supposed to be due mainly to the decrease of the soil stiffness with the density reduction. It was found from the experimental results that the compressibility index is a function of suction. The value of λ(s) decreased with increasing suction. This behaviour is consistent with the model of [21] who proposed that the slope of isotropic normal consolidation line λ(s) decreases monotonically with increasing suction from saturation condition. The Basic Barcelona Model was then adopted to get the theoretical compression index with suction. Results are given together with the experimental data (Fig.13): a fast decrease of λ can be appreciated with the suction increase, until reaching an asymptotic value (compressibility index reduction≈50%). The study performed by [35] on the Jossigny silt also led to the observation of a gently decrease of λ (about 10%) within a wide suction range 0→1600kPa. These outcomes find good agreement with the experimental results of the current research. Similar considerations were accomplished by [36] for unsaturated silt tested using an osmotic controlled-suction apparatus (Fig.13): also in that case, the compressibility index slowly decreased (approx. 75%) with the same suction range from 0kPa to 1600kPa.

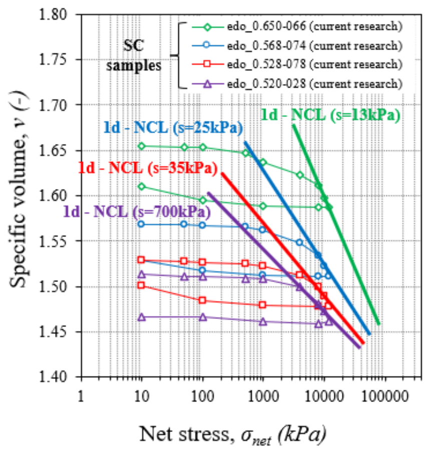

Figure 11. Stava tailings: influence of the suction on the 1d-NCL.

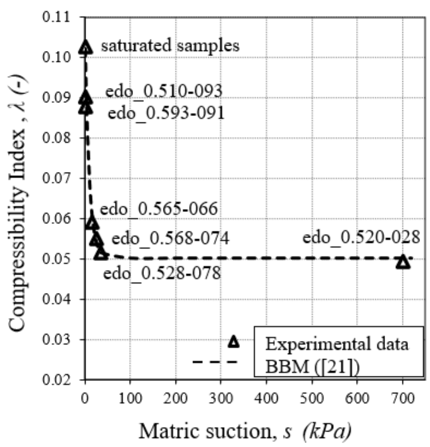

Figure 12. Stava tailings: experimental/theoretical compressibility index as predicted by the BBM.

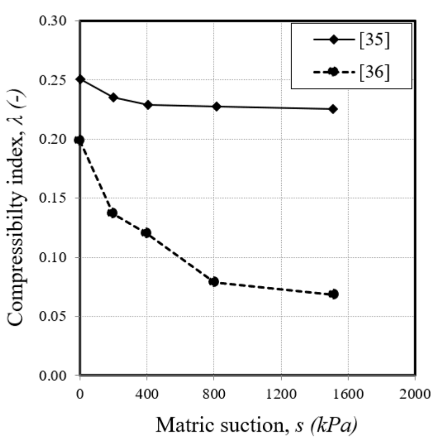

Figure 13. Literature data: influence of the matric suction on the compressibility index of silt ([35-36]).

The recompression index on the Stava tailings was also estimated, showing a maximum value for the fully saturated samples (k=0.01), and then decreasing with suction with minimum values k=0.001, as shown in Fig.15. In general terms, these results can be compared with those obtained by [37] for the unsaturated Po silt for a wider suction range. The authors performed isotropic tests using two suction-controlled devices, a triaxial cell and a resonant column torsional shear cell. In that case, a more gently decrease of the recompression index with suction was observed.

Finally, the LC yield curve was computed from the yield points given by the isotropic consolidation curves as shown in Fig.14. Starting from the yielding stress under fully saturated conditions, an increase with suction was observed. The shape of the LC yield curve is consistent with that proposed in the [21] model and it is also in good accordance with the results of researchers such as [22] and [38].

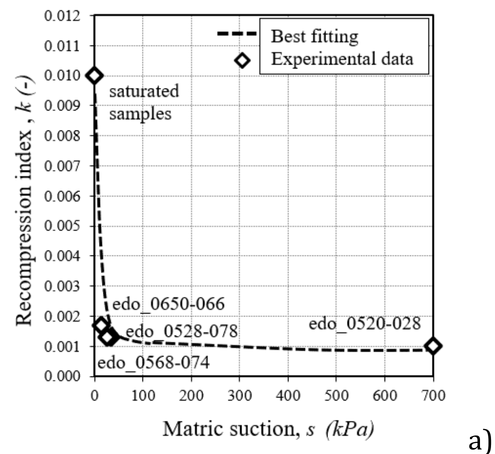

Figure 14. Stava tailings: evolution of the recompression index with suction.

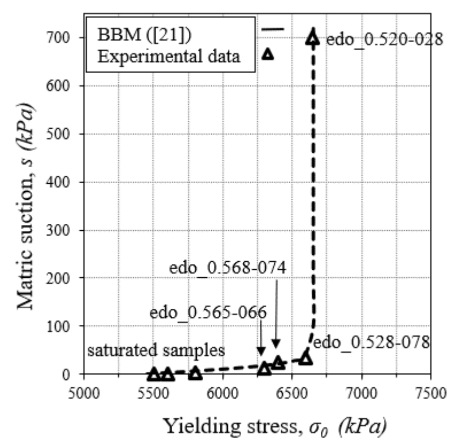

Figure 15. Stava tailings: yielding stress with suction according to the BBM and experimental data.

5. Conclusion

Results from an experimental program consisting of a series of oedometric tests were used to investigate the effect of suction on subsequent mechanical behaviour of unsaturated silty tailings. Based on the test results the following conclusions can be drawn:

- Experimental evidence led to state that the sample preparation method has no relevant effects on the transitional behaviour of Stava silty tailings tested under fully saturated conditions. On the other hand, non-unique Normal Compression Lines were observed if different initial densities samples were compressed under unsaturated conditions, and results compared with an extensive literature evidence still showing contrasting results depending on the ore tailings or the preparation techniques.
- The compression index of Stava tailings was observed to decrease with suction, according to the Basic Barcelona Model and with literature data on silty soils. The Basic Barcelona Model was then used to estimate the variation of the yield stress with suction, which was proved to increase with suction. The yield point has important role in the behaviour of unsaturated soils. Indeed, yield point due to increasing suction can be considered as a boundary beyond which the effect of suction on strength of soil is insignificant.
- The suction level of each compression test was estimated by knowledge of the water retention curve obtained from previous experimental studies on the same tailings.

Following the outcome obtained in this study, additional research under unsaturated conditions could cover a larger domain of mixtures made up of silty and sandy tailings to better simulate the heterogeneity of the in-situ tailings, or other preparation methods (i.e. water or air pluviation, wet compaction). A wider suction range may be tested to reproduce the real environment, or the aging effects (i.e. rearrangements, macro-interlocking or the cementation of the particles) could be considered, together with the effect of the temperature.

6. Acknowledgement

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