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Preliminary Evaluation of the Effects of the Unsaturated Conditions on the Pre-Shearing State of Stress of Quarzitic Tailings

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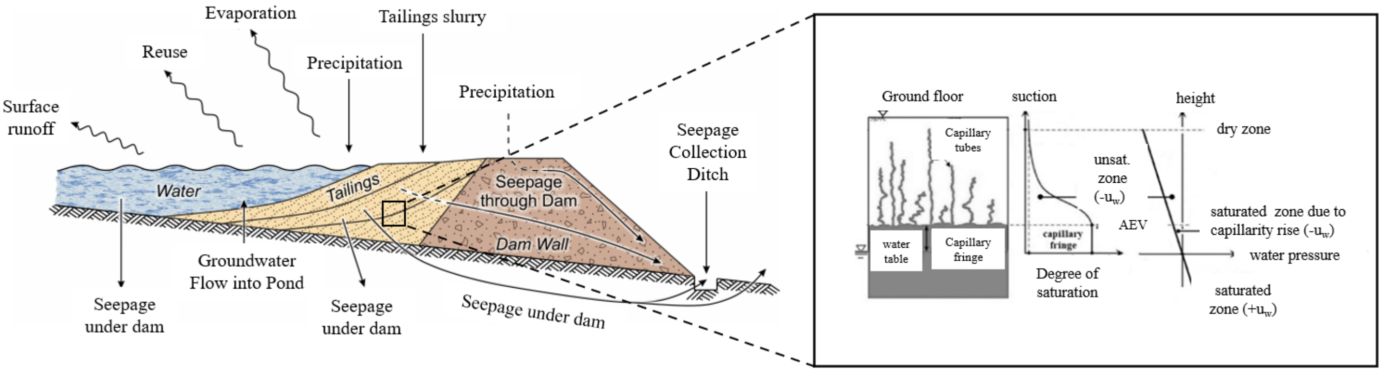
Abstract **-** This paper deals with the laboratory investigation of the compressibility of a silty soil, representative of tailing wastes, under unsaturated conditions. The experimental activity consisted of a series of conventional oedometer tests to analyse the stress-strain response at variable suction levels, and a series of water retention tests to determine the water retention curves to be later used for the theoretical interpretation, which was conducted according to the Barcelona Basic Model (BBM). The dependency of the soil compressibility, 1d-Normal Compression Line (1d-NCL), pre-consolidation stress and recompression index on the matric suction is preliminarily analysed. Both the compression and recompression indexes of Stava tailings were observed to decrease with suction. The experimental evidence also showed an increase of the pre-consolidation stress with suction, and the results find a good agreement with literature data obtained on more standard soils.

Keywords**:** tailings; unsaturated soil; compressibility; 1d-Normal Compression Line; pre-consolidation stress.

1. Introduction

Mines build tailing storage facilities (TSF) to safely store tailing wastes both during mining and after operations cease. Consisting of mixtures of processing fluids and finely ground rocks with a grading ranging from sand to clay/silt size, tailings have the consistency of a slurry, or paste, depending on the handling given to the slurries at the end of the separation processes of the mineral extraction. Also known as "tailing dams", TSFs are complex geotechnical structures (Fig.1) and deep knowledge of tailings response under unsaturated conditions represents an essential tool to understand the effects of the atmospheric interaction with TSF stability ([1]-[6]).



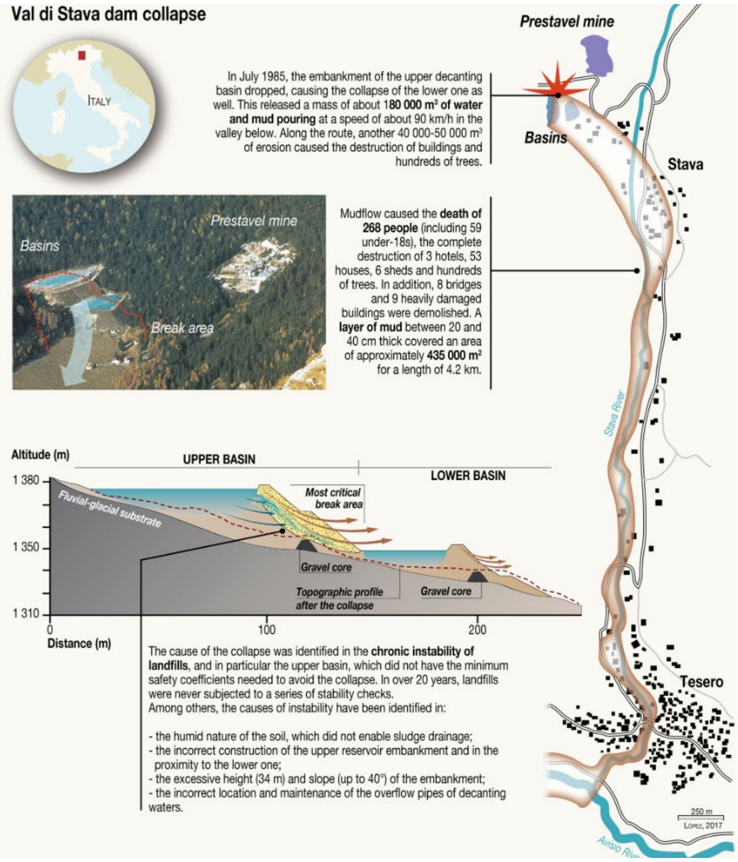
a) b)

Fig. 1: a) Cross section of a typical tailing dam; b) Unsaturated conditions and pore water pressure profile (modified from [1] and [5]).

Moving from these reasons, this study gives the main overcome of an experimental campaign to investigate some relevant aspects of the hydro-mechanical behaviour of unsaturated silty tailings. The pre-shearing state of stress is investigated by carrying out oedometer tests and water retention tests. A preliminary insight is given to outline the effects of the suction on the stress-strain response mainly in terms of compressibility and 1D-NCL on tailings. This issue is relevant for engineering applications as it offers the possibility of considering the effect of unsaturated conditions (pre-shearing state of stress, shear stiffness of the soil), which under static or dynamic conditions, affects the deformation behavior of tailing dam and - when modeled numerically - will result in a more accurate evaluation of their safety ([7]).

2. Soil characterization

The soil was collected from the upper Stava tailing dam after the collapse occurred in 1985. Built one above the other on a natural slope near the city of Stava (northern Italy), the two dams were aimed to store the waste products resulting from the mining activities of Prestavel fluorite plants (Fig.2). The experimental campaign was carried out at the soil testing laboratory of Politecnico di Torino (Italy) and the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) on the silty fraction passing through ASTM sieve n°200 (Fig.3). Geotechnical properties are summarized in Table 1, while the X-ray diffraction analysis allowed to identify quartz, calcite and fluorite as the main mineral components ([8]-[9]-[10]).



In July 1985, the embankment of the upper decanting basin dropped, causing the collapse of the lower one as well. This released a mass of about **180 000 m³ of water and mud pouring** at a speed of about 90 km/h in the valley below. Along the route, another 40 000-50 000 m³ of erosion caused the destruction of buildings and hundreds of trees.

Mudflow caused the **death of 268 people** (including 59 under-18s), the complete destruction of 3 hotels, 53 houses, 6 sheds and hundreds of trees. In addition, 8 bridges and 9 heavily damaged buildings were demolished. A **layer of mud** between 20 and 40 cm thick covered an area of approximately **435 000 m²** for a length of 4.2 km.

The cause of the collapse was identified in the **chronic instability of landfills**, and in particular the upper basin, which did not have the minimum safety coefficients needed to avoid the collapse. In over 20 years, landfills were never subjected to a series of stability checks.
Among others, the causes of instability have been identified in:

- the humid nature of the soil, which did not enable sludge drainage;
- the incorrect construction of the upper reservoir embankment and in the proximity to the lower one;
- the excessive height (34 m) and slope (up to 40°) of the embankment;
- the incorrect location and maintenance of the overflow pipes of decanting waters.

Fig. 2: Stava tailing dams collapse ([11]).

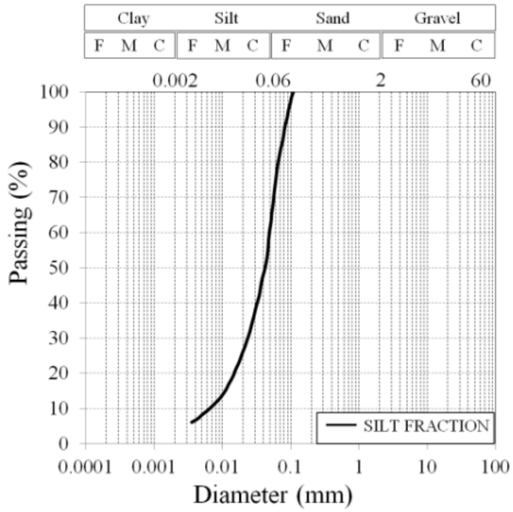


Fig. 3: Grain size distribution curves of the silty fraction of Stava tailings.

Table 1: Geotechnical properties of Stava silty fraction.

Properties	w_L (%)	w_P (%)	IP (-)	Gs (-)	K (m/s)
Silty fraction	27.4	18.0	9.4	2.82	10^{-7}

3. Testing apparatus and experimental techniques

3.1 Oedometric tests

A series of conventional oedometric tests were carried out to study the effect of the unsaturated conditions on the mechanical response of Stava silts, mainly in terms of compressibility, pre-consolidation stress, and recompression index. Statically compacted, cylindrical specimens (d=50mm h=20mm) were prepared by imposing different degrees of saturation.

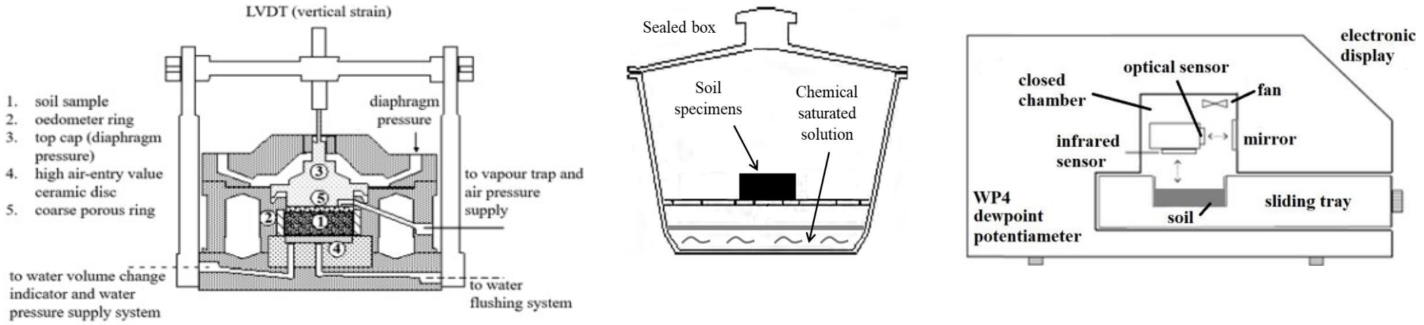
Samples were prepared by hand-mixing a well-known amount of dry soil with demineralized, de-aired water to obtain the desired initial water content. The mixture was statically compacted by applying an axial force to reach a certain volume. The same technique was adopted by previous studies performed by [13] on Stava silty samples under saturated conditions. The oedometric tests on unsaturated samples were carried out by using a conventional oedometer cell under constant water content conditions. A mass-based analysis performed at the end of each test allowed to verify that no water content variations occurred during the entire test consisting of an axial loading sequence followed by an unloading path. Linear variable differential transducer (LVDT) allowed to measurement of the axial displacements experienced by the samples during the test. Table 2 lists the unsaturated samples tested in the current research and the initial state of the saturated samples tested by [13].

Table 2. Initial state of Stava silty sample: void ratio, degree of saturation, dry unit weight and maximum vertical stress.

Sample	e_0 (-)	Sr_0 (%)	γ_d (kN/m^3)	σ_v (kPa)	Comments
edo_0.528-078	0.528	78.0	18.4	12’000	Current research
edo_0.568-074	0.568	74.0	17.9	12’000	
edo_0.650-066	0.650	66.0	17.0	12’000	
edo_028	0.772	100.0	15.9	10’001	[13]
edo_020	0.885	100.0	14.9	14’165	
edo_019	0.925	100.0	14.6	14’165	
edo_018	0.750	100.0	16.1	8’042	
edo_017	0.930	100.0	14.6	8’042	

3.2 Water retention tests

The suction level reached by Stava samples during the loading phase was estimated based on the water retention curves (WRC) evaluated on the same soil. The latter were obtained by carrying out water retention tests based both on techniques where the suction was imposed and the water content was measured (‘axis translation technique’ ATT, ‘vapour equilibrium technique’ VET), and on tests where the water content was imposed, and the suction was measured (‘dew point technique’ DPT). The axis translation technique was applied into a suction-controlled oedometer cell (Fig.4a) on samples 50mm diameter and 20mm height (Fig.2a). The vapour equilibrium and dew point measurements were performed, respectively, into a relative humidity-controlled sealed box (Fig.4b) and by using a chilled-mirror psychrometer (Fig.4c) on samples 20mm diameter, 10mm height. More details are provided in [4].



(a) (b) (c)

Fig. 4: Water retention test devices: (a) Suction-controlled oedometer cell (modified from [14]); (b) equipment used to apply the vapour equilibrium technique; (c) Chilled-mirror psychrometer for dew-point technique (modified from [15]).

4. Experimental results

The water retention tests allowed to experimentally obtain the relationship between suction and degree of saturation (or water ratio, or water content). The experimental points were fitted by adopting the model proposed by [16] to account for variation of the void ratio:

$$\mathrm{Sr} = \frac{1}{(1 + [\Phi(\nu - 1)^{\Psi} s]^{n})^{m}} \tag{1}$$

where Φ (kPa^{-1}) and n, m, ψ are dimensionless parameters to be calibrated, and v is the specific volume (Tab.3). Because of the constant water content conditions imposed during the oedometer tests, a vertical hydraulic path can be assumed on the WRC crossing the two main wetting branches evaluated at a void ratio corresponding to the begin (e_i) and at the end (e_f) of the compression curve. The suction levels s_1 and s_2 are then obtained, and the suction average value is adopted (Fig.5).

Table 3a. WRC parameters adopted for the main drying branch.

Main drying branch			
n (-)	m (-)	Φ (kPa^{-1})	Ψ (-)
1.67	0.40	0.28	5.32

Table 3b. WRC parameters adopted for the main wetting branch.

Main wetting branch			
n (-)	m (-)	Φ (kPa^{-1})	Ψ (-)
1.50	0.33	5.40	7.81

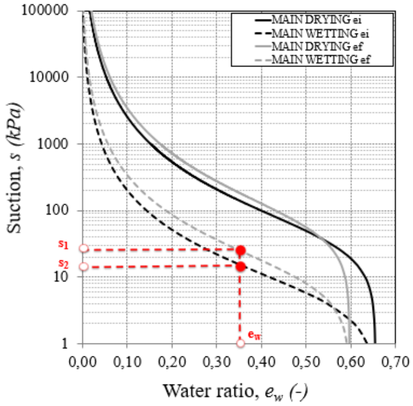


Fig. 5: Evaluation of the suction level by the WRC.

The 1d-NCL corresponding at different saturation conditions are shown in Fig.6 for the three unsaturated samples tested in the current research: an increase in the soil compressibility can be observed as the suction decreases, in good agreement with the Basic Barcelona Model. The lower compressibility index λ = 0.052 was obtained for the sample edo_0.528-078 associated with the highest suction (s=35kPa), while the higher compressibility index λ = 0.059 was given for the sample edo_0.650-066 related to the lowest suction values s=13 kPa. The oedometric tests performed by [13] on saturated Stava samples are given in Fig.7: a unique 1d-NCL was obtained, associated with a compressibility index λ approx. 0.104 because of the fully saturated conditions. According to [17], this latter value is higher than those obtained in the current research because of the influence of the saturation conditions on the soil stiffness.

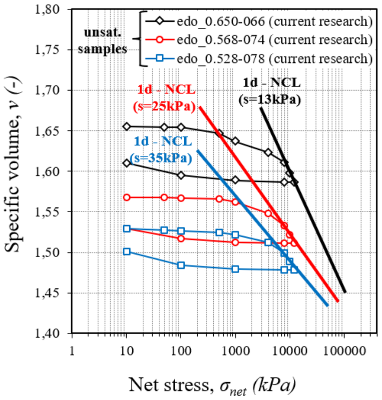


Fig. 6: 1d Normal Compression Lines depending on the suction level for the unsaturated Stava samples (modified from [18]).

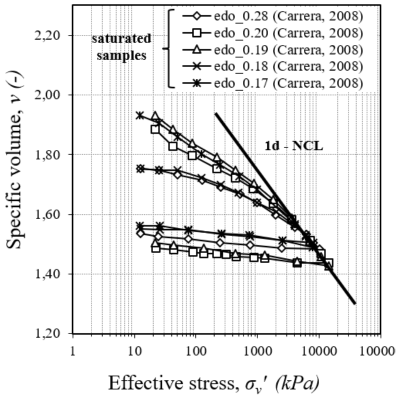


Fig. 7: 1d Normal Compression Lines for saturated samples tested by [13].

The experimental data in terms of soil compressibility are then fitted by using the Basic Barcelona Model and the evolution of the compression index with suction is evaluated. A decrease of the compressibility index with suction can be observed with a minimum value at suction no less than 40-50 kPa (Fig.8). The above outcomes on the Stava tailings find a good agreement with literature data concerning more standard soils. Indeed, the study performed by [19] on Jossigny silt gave a decrease in the compressibility index within a suction range between 0-1600 kPa. Similar results were obtained by [20] for an unsaturated silt tested through an osmotic controlled-suction apparatus. A suction increase led to a compressibility decrease also for the unsaturated Po silt tested by using a triaxial cell and a resonant column torsional shear device, as shown in Fig.9 ([21]).

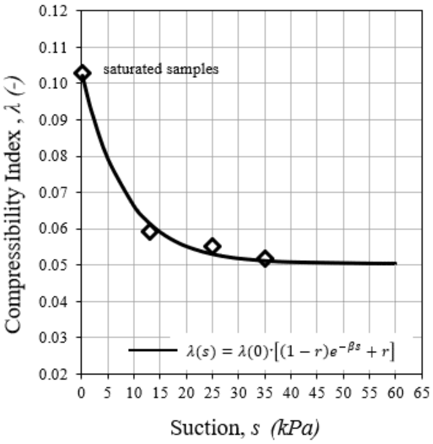


Fig. 8: Stava silty tailings: evolution of the compressibility index with suction.

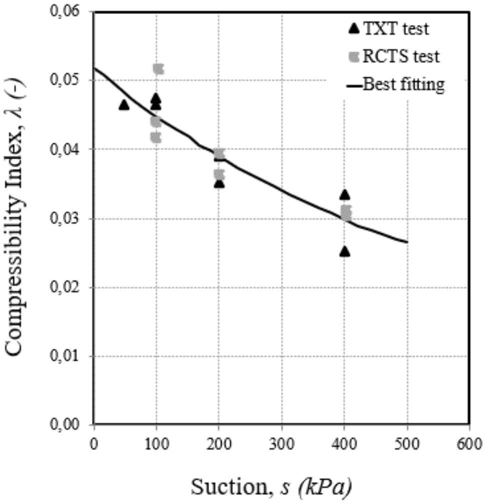


Fig. 9: Po silt: evolution of the compressibility index with suction (modified from [21]).

Table 4. Stava silty tailings: list of matric suction level, compressibility index, recompression index and pre-consolidation stress.

Sample	s (kPa)	λ (-)	k (-)	σ_P (kPa)	Authors
edo_0.528-78	35.0	0.052	0.0013	6600	Current research
edo_0.568-074	25.0	0.055	0.0013	6400	
edo_0.650-066	13.0	0.059	0.0017	6300	
edo_028	≈ 0	0.104	0.0100	5500	[13]
edo_020					
edo_019					
edo_018					
edo_017					

The recompression index on Stava tailings was also estimated, resulting higher for fully saturated samples (k=0.01), and then showing a decrease with suction. Indeed, unsaturated samples led to lower values (k=0.001) as shown in Fig.12. In general terms, these results find a good agreement with those obtained by [21] for the unsaturated Po silt (Fig.13) for a wider suction range. The Basic Barcelona Model also allowed a preliminary evaluation of the yield stress (σ_0) of Stava tailings with suction:

$$\sigma_0 = \sigma_c \left(\frac{\sigma_c^*}{\sigma_c}\right)^{[\lambda(0)-\kappa]/[\lambda(s)-\kappa]} \tag{2}$$

where σ_c was the reference stress and σ^*_c the yielding stress at fully saturated conditions estimated by means of the Casagrande procedure. Also for Stava tailings, an increase in the yield stress with suction increase was observed, leading to obtaining the Loading Collapse Curve (Fig. 14).

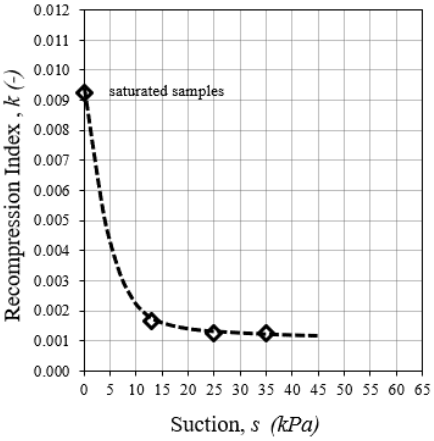


Fig.12

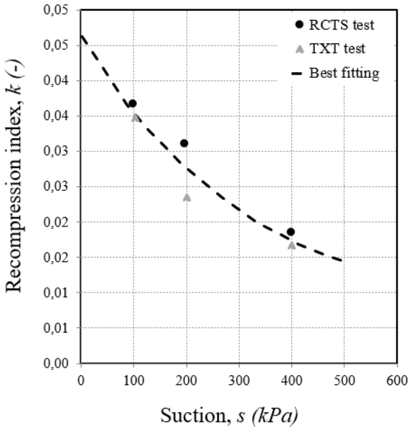


Fig.13

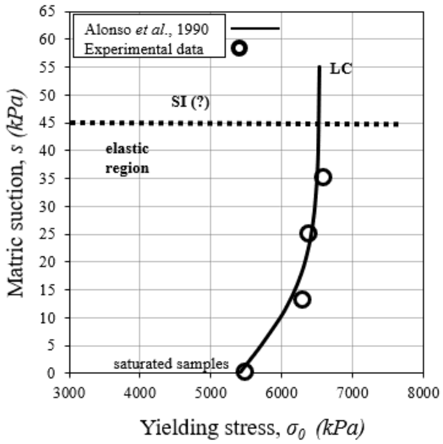


Fig.14

Fig. 12: Stava silty tailings: evolution of the recompression index with suction.

Fig. 13: Po silt: evolution of the recompression index with suction (modified from [21]).

Fig. 14: Stava silty tailings: evaluation of the yielding stress with suction.

6. Conclusions

Results from an experimental program consisting of a series of consolidation tests and water retention tests are used to investigate the effect of the unsaturated conditions on the mechanical behavior of the silty fraction of mining wastes. The mechanical response was studied in terms of 1d-NCL, yield stress, and compressibility indexes λ and k. Within the suction range investigated, both the compression index and the recompression index decrease with suction, meaning an increase in the soil stiffness when unsaturated conditions occur. The water retention curves were then estimated by using several types of non-standard, sophisticated equipment, as well as the axis translation, the vapour equilibrium method, and the chilled-mirror psychrometer. The WRC allowed the evaluation of the suction level reached during the oedometer consolidation tests. Moreover, the Basic Barcelona Model was used to estimate the variation of the compression of index and yield stress with suction. Within the suction range investigated, both the stiffness and yielding stress increased with suction. Finally, the experimental results on Stava tailings were successfully compared with the outcome described in the literature for standard soils. Following the preliminary outcome obtained in this research, additional studies under unsaturated conditions could cover a larger domain of gradings to better simulate the heterogeneity of in situ tailings. To reproduce the real environment, a wider suction range could be tested, together with the effect of the temperature or a wider range of suction.

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