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On the Coupled Hydro-Mechanical Behaviour of Tailings Under Unsaturated Conditions

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Abstract **-** The current research investigates some peculiarities of the hydro-mechanical response of mining wastes retrieved from the collapsed lower portion of the Stava upper basin (Italy). An experimental campaign of suction-controlled triaxial tests was carried out to study the hydro-mechanical behavior of the soil under different drainage conditions, suction levels, and net pressures. The hydraulic paths and volumetric response were interpreted accounting for the water retention curves experimentally obtained on the same tailings from a previous experimental campaign, thus confirming the coupling between the hydraulic and mechanical response of the unsaturated soil sheared under both drained and undrained conditions. A Critical State condition was reached for many samples, and the outcomes were compared with those obtained on the same soil tested under saturated conditions. By adopting a Bishop-like effective stress, within the suction range investigated, it was found that the soil strength is characterized by a single Critical State Line both under saturated and unsaturated conditions.

Keywords**:** unsaturated soil, tailings, suction-controlled triaxial tests, WRC, suction.

1. Introduction

Tailings are the waste resulting from mineral processing that are commonly stored in impoundments which are commonly retained by embankments (‘tailings storage facilities’). The collapse of these structures may result in casualties, severe economic costs environmental impacts as evidenced by recent failures in Brazil, Tanzania, and South Africa ([1], [2], [3], [4]). A deep knowledge of the hydro-mechanical response of such soils under unsaturated conditions is widely recognized as a key tool to perform reliable stability analyses of tailing dams. This research shows some significant experimental results of a testing campaign carried out on the Stava tailings. Suction-controlled triaxial tests allowed to investigate the hydro-mechanical behavior of the silty fraction. The hydraulic paths and the volumetric behaviour were successfully interpreted accounting for the water retention curves previously obtained on the same silty tailings, leading to confirm the coupling between the hydraulic and mechanical behaviour of the soil under unsaturated state.

2. Material characterization and laboratory device

The soil was collected from the upper Stava tailing embankment after its collapse occurred in 1985, Italy (Fig.1a). The experimental investigation was carried out at the soil testing laboratory of Politecnico di Torino on the silt fraction passing through a mesh sieve n°200. Its grain size distribution is given in Fig 1b, while liquid limit (w_L=27.4%) and plastic limit (w_P=18.0%) make the Stava silty tailings as a medium-low plasticity soil (PI=w_L-w_P =9.4%) with 8% in weight of clay size material. The specific gravity G_S=2.828 and hydraulic conductivity k=10^{-7}m/s make the Stava silty tailings a medium-low permeable, heavy soil. X-ray diffraction analysis allowed to identify the presence of quartz, calcite and fluorite as shown in Figure 1c ([5], [6]). Cylindrical specimens (Φ_i=38 mm; h_i=76 mm) were prepared at different water content and void ratio. A control axial displacement loading frame was used to statically compact the sample under controlled water content. Table 1 gives the initial state of the samples and the drainage conditions imposed during the shearing phase. As shown in Table 2, each suction-controlled, monotonic triaxial test consisted of three phases (Fig.2): i) suction equalization through the axis translation technique, ii) isotropic consolidation at constant suction, iii) shearing ([5], [7]). In some cases, this phase was preceded by an isotropic loading phase at constant water content. The second phase was performed by imposing different net pressures (difference between average tension and air pressure) ranging between 100 kPa and 800 kPa. The third phase was performed by increasing the axial load at constant water content (undrained conditions), or constant suction (drained conditions). In one case, the shearing was preceded by a wetting phase of the sample by increasing the water pressure. At the end of the shearing phase, the water content was determined according to [8], by weighing the sample with a balance having accuracy +/- 0.0001 g before and after drying in an oven at 105°C for 24 hours. Due to the unsaturated conditions, variations in the total volume of the sample and variations in the volume of water are not the same. Therefore, volume changes of the sample were assessed by taking regular laser scans of the sample profile throughout the duration of the test.

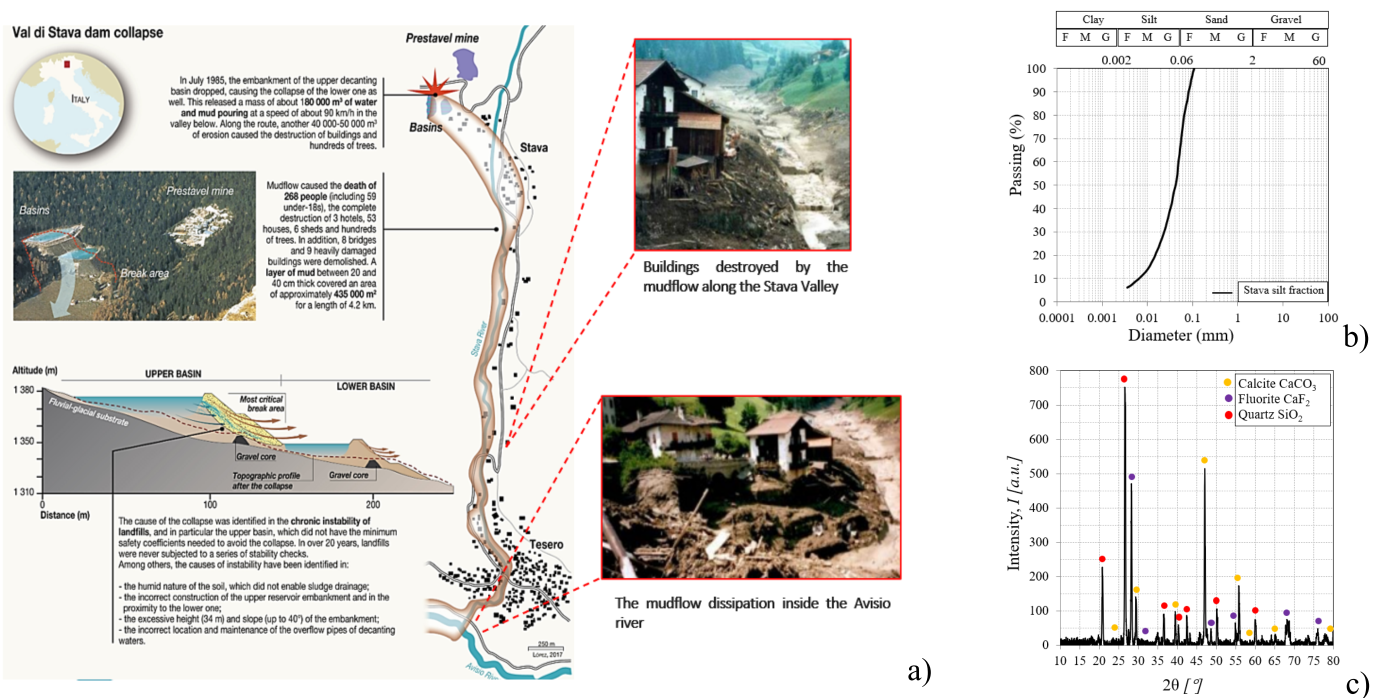


Fig. 1: a) Summary of the Val di Stava dam collapse ([9], [10]); b) grain size distribution of the Stava silty fraction and c) its XRD spectrum ([5], [6]).

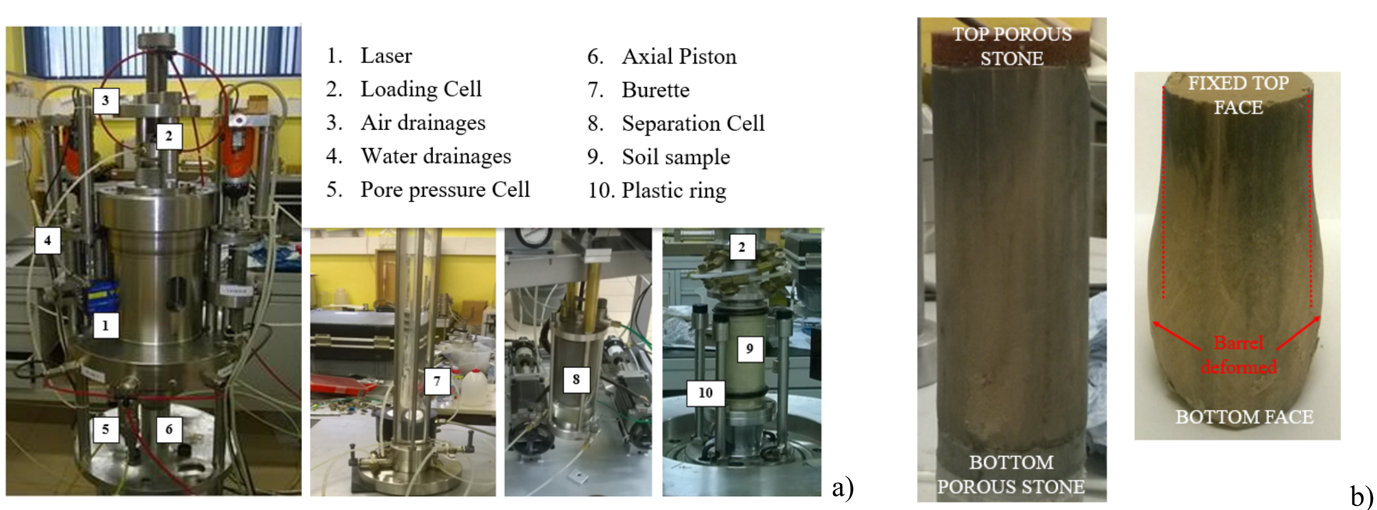


Fig. 2: a) Suction-controlled triaxial cell: main components (modified from [7] and [5]); b) Barrel deformed specimen 0.70-60-200 at the beginning and at the end of the suction-controlled test nr.2.

Some peculiarities of the outcomes obtained from the suction-controlled triaxial tests have been presented and interpreted as accounting for the water retention response of the same soil previously investigated by performing an extensive campaign of water retention tests ([11]). Thus, highlighting the coupling between the hydraulic and mechanical behavior of the soil under unsaturated conditions.

Table 1. Initial state of Stava samples: dry unit weight (γ_d), void ratio (e_0), water content (w_0), suction control technique (A.T.=axis translation technique, V.E.T.=vapour equilibrium technique), drainage conditions during the shearing phase, and comments A.=approached; R.=reached; N.R.=not reached ([5], [7]).

Test	Sample	γ_d (kN/m^3)	e_0 (-)	w_0 (-)	Suction control technique	Drainage conditions	Critical State
1	0.70-60-100	16.60	0.70	14.90	A.T.	Undrained	A.
2	0.70-60-200	16.60	0.70	14.90	A.T.	Undrained	R.
3	0.70-60-400	16.60	0.70	14.90	A.T.	Undrained	R.
4	0.60-60-800	17.70	0.60	14.90	A.T.	Undrained	N.R.
5	0.80-90-800	15.70	0.80	5.70	A.T.	Undrained	R.
6	0.80-90-100	15.70	0.80	14.10	A.T.	Drained (suction imposed)	R.

Table 2. Suction-controlled triaxial tests: suction (s), deviatoric stress (q), net stress (p_{net}). M.=measured, C.=constant. ([5], [7]).

Test	Sample	Loading w=const	Suction equalization phase			Consolidation phase	Wetting phase			Shearing phase		
		p_{net} (kPa)	s (kPa)	q (kPa)	p_{net} (kPa)	p_{net} (kPa)	s (kPa)	q (kPa)	p_{net} (kPa)	s (kPa)	q (kPa)	p_{net} (kPa)
1	0.70-60-100	-	$s_i \rightarrow 60$	0	5-10	5→100	-	-	-	M.	M.	M.
2	0.70-60-200	-	$s_i \rightarrow 60$	0	5-10	5→200	-	-	-	M.	M.	M.
3	0.70-60-400	-	$s_i \rightarrow 60$	0	5-10	5→400	-	-	-	M.	M.	M.
4	0.60-60-800	-	$s_i \rightarrow 60$	0	5-10	5→800	60→20	C.(0)	C.(800)	M.	M.	M.
5	0.80-90-800	100	$s_i \rightarrow 90$	0	100	5→800	-	-	-	M.	M.	M.
6	0.80-90-100	100	$s_i \rightarrow 90$	0	100	-	-	-	-	C. (90)	M.	M.

3. Experimental results

3.1. Water retention tests

The retention properties of the Stava silty fraction were investigated by previous studies ([11], [12]). The water retention behavior of Stava tailings was found to extensively depend on the void ratio, fine content, sample preparation method, and such a dependency was interpreted through the expression proposed by [13]:

$$Sr = \frac{1}{\left(1 + \left[\Phi(v-1)^{\psi} s\right]^n\right)^m} \tag{1}$$

where v is the specific volume and n, m, ψ, Φ are soil model parameters summarized in Table 3, while the dependency of the main drying curves on the void ratios of interest for the current study is given in Fig. 3 by the water retention curve (WRC) on the e_w-s plane:

$$e_w = Sr \cdot e \tag{2}$$

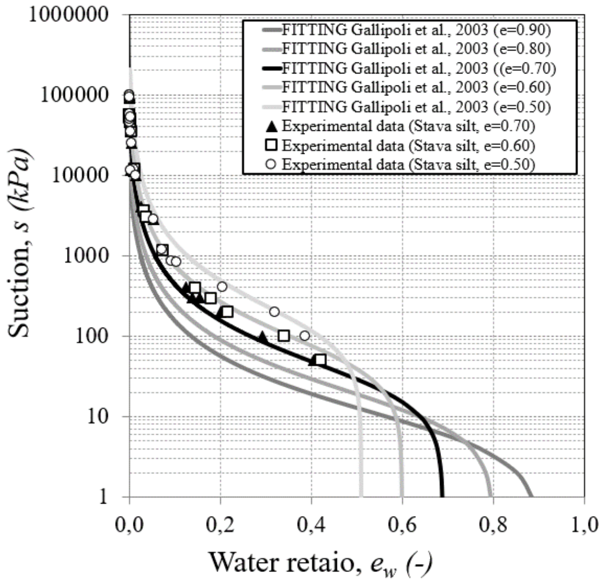


Fig. 3: Main drying branches: influence of void ratio on the water retention behavior of the Stava silty tailings (modified from [11], [12]).

Table 3. Parameters of the water retention model proposed by [13] for the Stava silty tailings (main drying branch and main wetting branch).

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

(part 1/2)

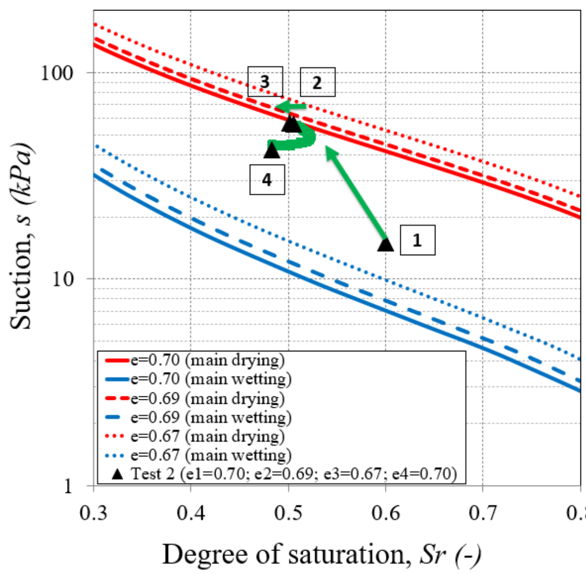
Main wetting branch			
n (-)	m (-)	Φ (kPa^{-1})	Ψ (-)
1.50	0.33	5.40	7.81

(part 2/2)

3.2. Suction-controlled triaxial tests

The hydraulic path of the sample 0.70-60-200 is given in Fig. 3 in terms of suction and degree of saturation. The different test phases correspond at black triangles: initial state (1), end of suction equalization phase (2), end of consolidation phase (3), and end of shearing phase (4). The drying-wetting path that occurred during the shearing phase is represented by the green line, from point 3 to point 4. The degree of saturation first increased because of the initial volume contraction during shearing at constant water content. Then, when the sample started to increase its volume until the end of the test, the effective degree of saturation decreased. The entire path lies inside the water retention curve, in which drying and wetting branches are evaluated at different void ratios experimented by the sample during the entire suction-controlled triaxial test. Therefore, the so-estimated WRC can be assumed as a region within the hydraulic paths - derived from the suction-controlled triaxial tests - could exist. Similar considerations can be made for the hydraulic path resulting from sample 0.80-90-100 shown in Fig. 4, thus confirming the coupling between hydraulic and mechanical behavior under unsaturated conditions. The entire hydraulic paths of the suction-controlled triaxial tests are given in Fig. 5. They are represented by circles on the (e-e_w) plane, providing an equivalent representation of that given in Fig. 3-4. The iso-degree of saturation dotted curves have been obtained by varying the water ratio at a certain degree of saturation. It is possible to state that all hydraulic paths are quite close to the degree of saturation reached during the tests. The 2D graphs given in Fig. 3-4-5 are a simplified representation of the WRC surface that can be defined into the three-dimensional space (s-Sr-e) or (s-e-e_w). Therefore, if the triaxial hydraulic paths are plotted into the 3D space defined by the WRC - obtained from eater retention tests and properly calibrated within a wide range of void ratios (Tab. 3) - it is clear how the WRC represents a three-dimensional domain within the hydraulic paths could exist (Fig. 6).

The volumetric response of the samples resulting from the suction-controlled triaxial test can also be interpreted by considering the evolution of the water retention curve. During the shear phase of the sample 0.80-90-100, the suction is kept constant because of the imposed drained conditions. The sample shows a purely contractive behavior until Critical State conditions are reached (Fig. 7), and its hydraulic path - represented by the green arrow - is shown in Figure 8 together with the main branches of the WRC calibrated at void ratios reached during the test nr.6. Since the drained conditions and the contractive behavior, the sample loses some water, but the volume reduction is greater than the exchanged water volume. Therefore, the hydraulic path moves horizontally - because of the drained conditions - within the WRC domain represented by the drying and wetting branches (Fig. 8). During the undrained shearing phase, sample 0.60-60-800 - together with a suction increase - shows a certain volume reduction followed by a dilatative response (Fig. 9), despite the Critical State is not fully reached. Figure 10 shows the hydraulic path (green arrow) with the respective main branches of the WRC calibrated at void ratios reached during test nr.4. The initial state of the sample is the point A and lies on the wetting branch e=0.57 because of the imbibition imposed after consolidation. Based on the saturated soil mechanics principles, under constant water content conditions and dilatant behavior, pressures are expected to decrease (i.e., suction increases). This happens even under unsaturated conditions: during the undrained shear, the hydraulic path moves upward (w=const. → e_w=const.) to reach the main drying branch e=0.58 resulting in an increased suction.



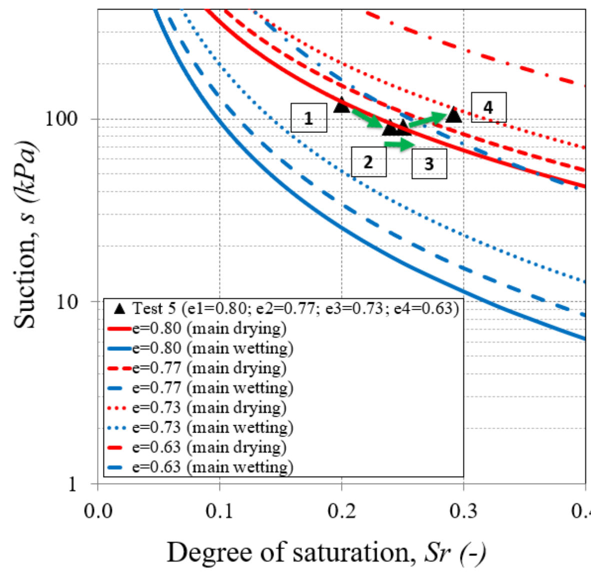


Fig. 3: Sample 0.70-60-200 - Superposition of the WRC and the hydraulic path obtained from the suction-controlled triaxial test.

Fig. 4: Sample 0.80-90-800 - Superposition of the WRC and the hydraulic path obtained from the suction-controlled triaxial test.

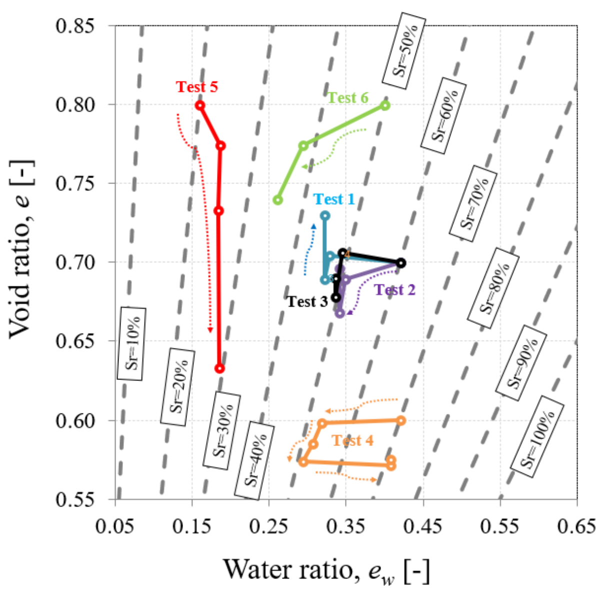


Fig. 5: Schematized hydraulic paths of all the samples into the (e-e_w) plane.

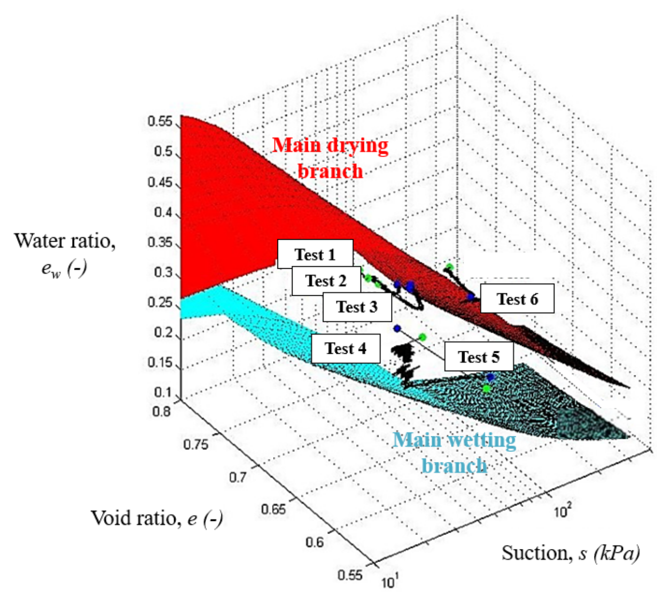


Fig. 6: Water retention curve and hydraulic paths obtained from suction-controlled triaxial tests (modified from [5], [7]).

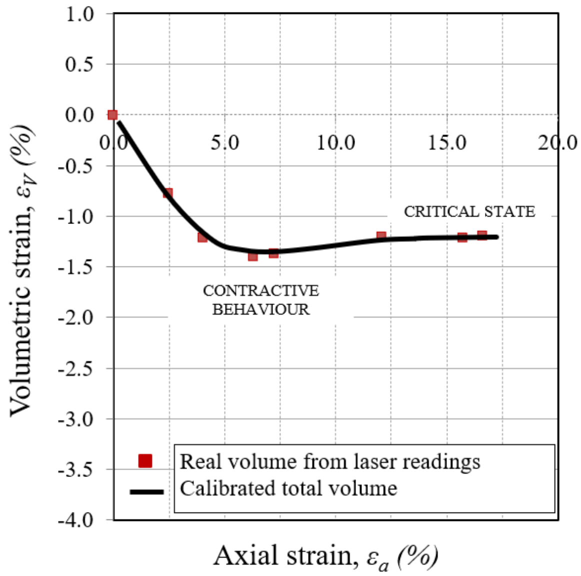


Fig. 7: Shearing phase, sample 0.80-90-100 - Stress-strain Curve (modified from [5]).

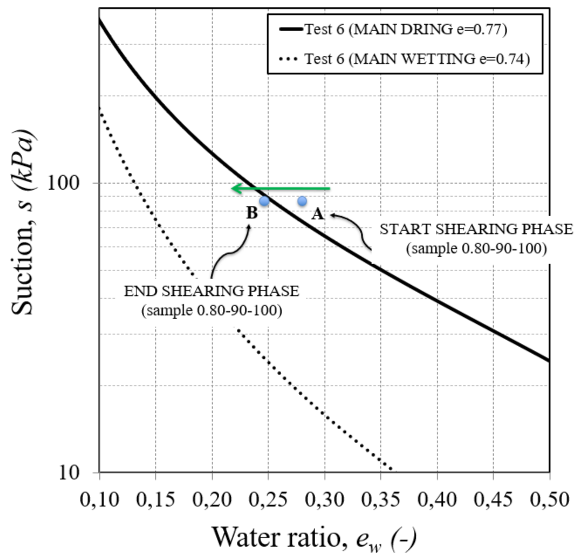


Fig. 8: Shearing phase, sample 0.80-90-100 - Hydraulic path and its domain represented by the WRC (modified from [5]).

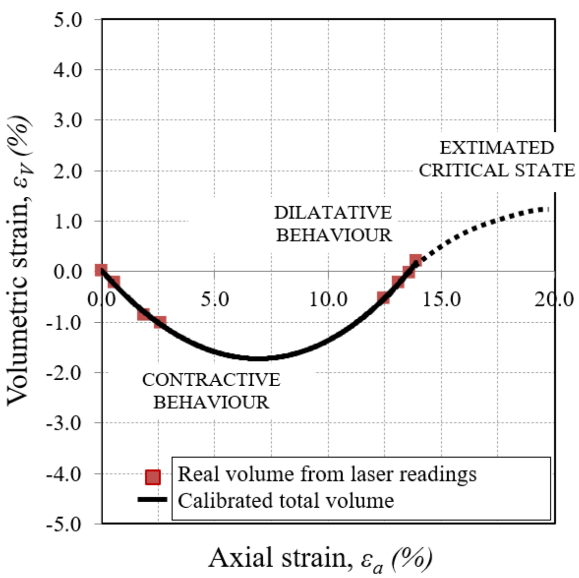


Fig. 9: Shearing phase, sample 0.60-60-800 - Stress-strain curve (modified from [5]).

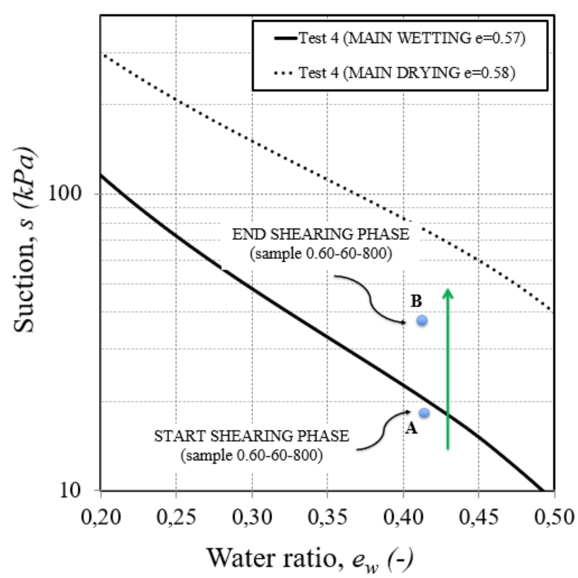


Fig. 10: Shearing phase, sample 0.60-60-800 - Hydraulic path and its domain represented by the WRC (modified from [5]).

The final state of the triaxial tests is given in Fig. 11: the deviator stress q at the end of the shearing phase is reported with the mean Bishop stress p'_B:

$$p'_B = p'_{net} + \chi \cdot s \tag{3}$$

where p'_{net} is the net pressure (difference between average tension and air pressure), and the χ parameter is assumed to be equal to the degree of saturation ([14]). The final state of the same soil monotonically sheared by [6] and [15] under saturated conditions is provided by the red squares. The two sets of data lie in quite a narrow area around a unique CSL identified by the solid double line. Such experimental results suggest that, for the interval of stresses investigated in the current research, the "bonding effect" due to water menisci and to the matric suction seems to play not a relevant effect on the shear strength at critical state conditions. Similar results were obtained by [16]. The Authors performed a hydro-mechanical characterization campaign on normal-consolidated and over-consolidated pyroclastic silty-sand through triaxial tests in saturated conditions (drained shearing phase) phase, and suction-controlled triaxial tests at different mean net stresses, suction levels, and void ratios. In both cases, for saturated and unsaturated silty-sand samples, they observed that the data in terms of deviator stress and effective stress were quite aligned, so they identified a Critical State Line having a unique slope. Even if the suction seemed not to significantly affect the hydro-mechanical behavior of the soil, the experimental data obtained by [16] showed that the saturation conditions have a certain impact on the stress-strain curve: saturated normal-consolidated specimens showed lower values of dilatancy than the unsaturated specimens. Similar results have been reported by other authors [17] on compacted silt, [18] on compacted non-active clay, [19] on residual clayey soils, [20] on aged compacted clay, and [21] on compacted silt.

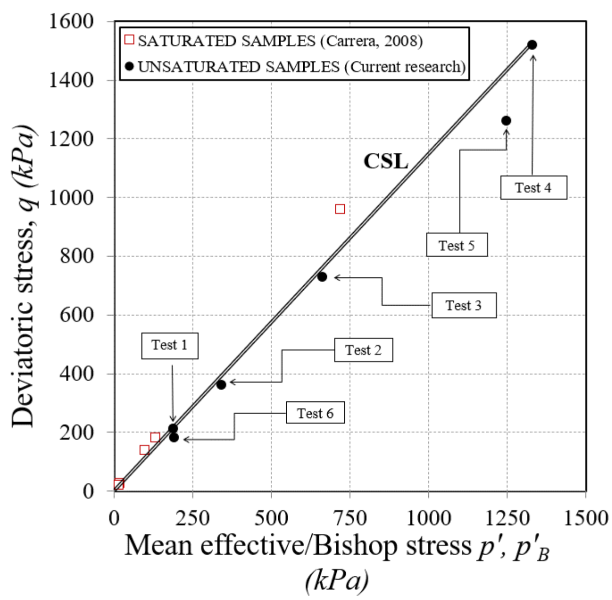


Fig. 11: Critical State Line for saturated silt samples and unsaturated Silty Stava samples (modified from [5] and [6]).

4. Conclusion

A thorough comprehension of the hydro-mechanical behavior of tailings under unsaturated conditions is essential for addressing stability issues in tailing dams. Partially saturated silty tailings were analysed through water retention and suction-controlled triaxial tests conducted under constant water content and constant suction scenarios. Given the interaction between hydraulic and mechanical behavior in unsaturated states, the water retention curve appears to define a region where hydraulic paths may occur. Additionally, volume changes were studied and effectively explained using the WRC. Finally, the results were compared with those from a previous experimental series on the same soil under fully saturated conditions. Within the suction range investigated, the strength of the silty Stava tailings can be assumed as governed by a single Critical State Line in both saturated and unsaturated states.

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