

An Insight into the Hydraulic Response of Unsaturated Sand-Silt Mixtures of Stava Tailings

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Abstract - This research provides the main outcomes of an experimental investigation into the water retention behaviour of unsaturated tailing wastes collected after the failure of the Stava tailing dams. The water retention response of Stava tailings is studied by carrying out tests which apply different techniques, respectively the axis translation method, the vapour equilibrium technique and the dew-point method. The dependency of the Water Retention Curve (WRC), relative hydraulic conductivity and apparent cohesion on the grain size distribution, and on the initial void ratio was investigated to account the in-situ heterogeneity of tailing wastes. As for standard soils, looser tailing specimens showed a lower water retention capability than that given in the denser ones. Similarly, the reduction of the fine content showed to decrease in the water retention capability of tailings. A microstructural interpretation in terms of the cumulative value of the pore size density (PSD) is also provided. The in-depth knowledge of the hydro-mechanical response of the soils proposed by the current research finds its practical application as a fundamental tool to reliably assess the stability of the tailing storage facilities which the high rate of recent collapses poses unacceptable fatalities with environmental and economic damages.

Keywords: Water retention curve, Tailings, Stava, Unsaturated soils.

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1. Introduction

Mechanical and hydraulic response in unsaturated conditions is coupled, therefore the accuracy in predicting the hydraulic soil behaviour is

essential for determining the mechanical soil response. The shear strength is affected by the pore fluid via its suction but also its degree of saturation so, different degrees of saturation associated to the same suction will lead to different values of shear strength ([1]. Moving from this reason, the current research is aimed at providing a preliminary insight into the range of hydraulic response of tailing materials by considering the variation in the void ratio and the fine content which could reasonably be expected in situ.

2. Testing material and experimental apparatus

The hydraulic behaviour was investigated by means of water retention tests carried out at Politecnico di Torino (Italy) on the tailing samples collected from the Stava upper embankment, which remained in place after the failure occurred in 1985. Tailings studied in the current research are composed of two grain sizes: a silt fraction passing through a sieve n°200 that seemed to be deposited inside the basin, and sand fraction made up of particles retained by sieve n°200 that was part of the embankment. The D₁₀, D₅₀ and D₉₀ of the sand fraction are equal, respectively, to 0.08 mm, 0.20 mm and 0.35 mm, ([2], with a specific gravity equal to 2.721. Liquid, plastic limits and specific gravity (GS) of the silty fraction are 27.4%, 18.0% and 2.828. X-ray diffraction analysis showed that both fractions were made up of quartz, with a significant amount of calcite and fluorite, especially within the silty fraction ([3], [4], [5]), with an absolute permeability equal to 9.5·10⁻⁶ m/s (sandy fraction and 10⁻⁷ m/s (silty fraction). All specimens were prepared at different initial void ratio or fine content, and statically compacted. The hydraulic behaviour was investigated

in terms of WRC by means of different methods (details are given in [3] and [6]):

- 1) axis translation technique applied into a suction-controlled oedometer (Figure 1) on samples 50 mm diameter and 20 mm initial height, and vapour equilibrium technique (Figure 2b) applied into a closed box on samples having initial size of 20 mm diameter and height of 10 mm;
- 2) dew-point technique (Figure 2a) applied by a chilled mirror psychrometer (WP4C) on samples having initial size of 20 mm diameter and height of 10 mm.

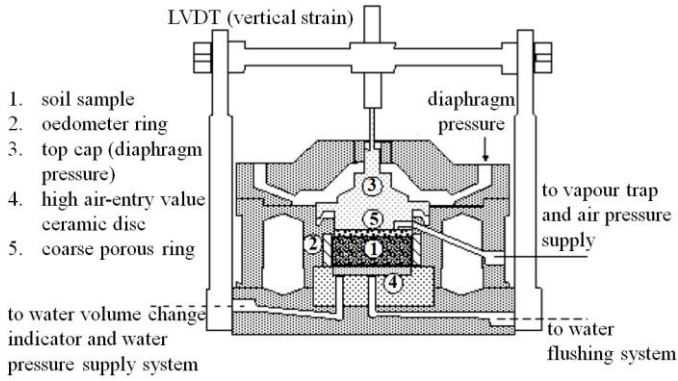


Figure 1. Schematic view of the suction-controlled oedometer (modified from [7]).

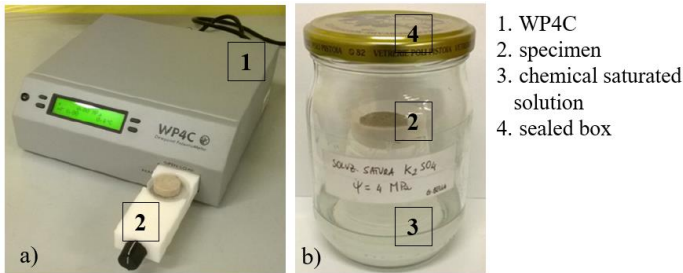


Figure 2. a) Dew-point potentiometer WP4C, b) equipment for the vapour equilibrium technique.

Table 1 gives the initial state of Stava samples in terms of void ratio (e_0), water content (w_0), degree of saturation (S_r) and dry weight (γ_d).

Table 1. Initial state of Stava samples.

Sample	e_0 (-)	w_0 (-)	S_r (%)	γ_d (kN/m ³)	Sand/ Silt (%)
SILT-0.7	0.7	17.3	70	16.6	0/100
SILT-0.6	0.6	15.0	70	17.6	0/100
SILT-0.5	0.5	15.9	90	18.9	0/100
7030-0.7	0.7	17.8	70	16.2	70/30
3070-0.6	0.6	17.2	80	17.4	30/70

3. Experimental results

Figure 3 shows the experimental results obtained from the three adopted techniques on sample SILT-0.6. The black diamond marked as " $s_i?$ " represents the assumed initial state of the specimen in terms of s and $S_{r_{eff}}$. Indeed, the initial degree of saturation has been imposed (70%) while the initial suction was unknown. Due to the wetting response of the sample at the imposed suction 50 kPa at the first step of the water retention test, the initial suction of SILT-0.6 was higher than that suction value. The experimental points were fitted by the van Genuchten model ([8], Table 2):

$$S_r = 1/[1 + (\alpha s)^n]^m \quad (1)$$

where α parameter is associated to the air entry value, while n and $m=1-(1/n)$ are dimensionless parameters. The effective degree of saturation was defined as $S_{r_{eff}} = (S_r - S_{r_{res}})/(1 - S_{r_{res}})$ allowing to obtain the main drying and the main wetting branches of the WRC ($S_{r_{res}} = 0.05$).

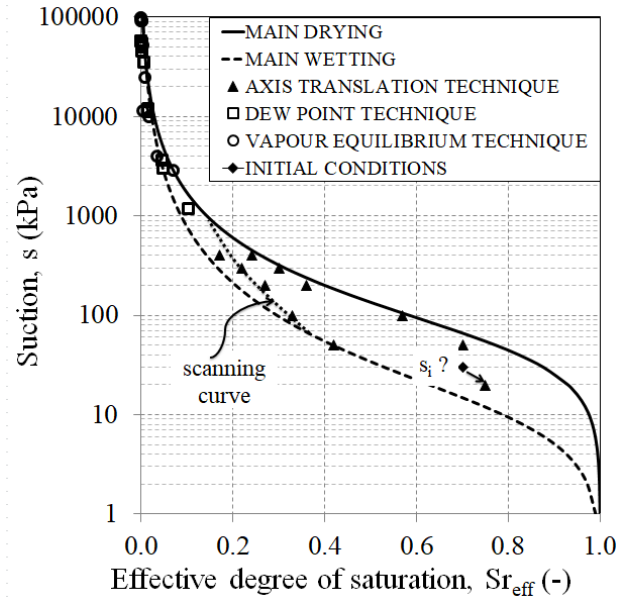


Figure 3. Sample SILT-0.6, experimental points, fitting Van Genuchten curve for the three applied methods.

Table 2. Van Genuchten parameters α (kPa⁻¹), n (-), m (-).

Sample	Main drying			Main wetting		
	α	n	m	α	n	m
SILT-0.7	0.042	1.62	0.38	0.32	1.50	0.33
SILT-0.6	0.019	1.65	0.39	0.10	1.52	0.34
SILT-0.5	0.009	1.67	0.40	0.06	1.52	0.34
7030-0.7	0.120	1.55	0.35	0.60	1.70	0.41
3070-0.6	0.021	1.68	0.40	0.15	1.54	0.35

The influence of the fine content on the WRC was investigated (Figure 4), giving that the main drying and wetting branches were affected by the soil grading.

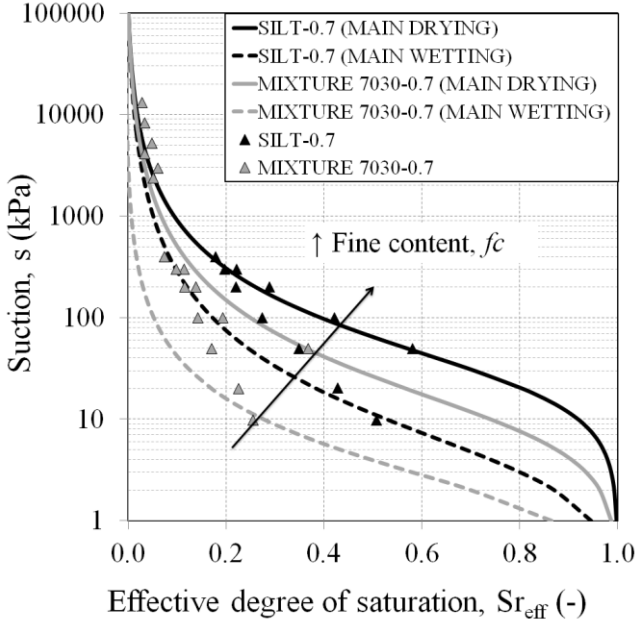


Figure 4. Influence of the fine content on the water retention behaviour.

A decrease of the fc implies a movement of the WRC to low suction values. Indeed, when decreasing the fine content, the pores between the sandy grains get emptied with the small silty particles resulting an overall higher permeability, and so a lower retention behaviour. A comparison of the air entry values (AEV) of the two samples show that the AEV of sample 7030-0.7 (8.3 kPa) is lower than that of SILT-0.7 (23.8 kPa).

According to Bishop & Blight, 1963 [9], the failure criteria of soils under unsaturated conditions is:

$$\tau_f = \sigma_n \cdot \tan(\varphi) + \chi \cdot s \cdot \tan(\varphi) \quad (2)$$

where τ_f is the shear strength, χ is the Bishop effective stress parameter, σ_n is the total normal stress and φ is the friction angle (according to [3] $\varphi = 33^\circ$). The second term, known as 'apparent cohesion', represents the increase of the shear strength due to the unsaturated conditions to include the effect of the capillarity inter-particle forces due to capillary mechanism ([10]). Assuming $\chi = Sr$ ([11]), the effect of the fine content on the apparent cohesion was preliminary estimated from knowledge of WRC for different effective degree of saturation levels (Figure 5). The apparent cohesion

showed to increase with the fine content (non-linearity was assumed) and, within the degree of saturation range investigated ($Sr=60\%-90\%$), it decreased with the increase of Sr_{eff} .

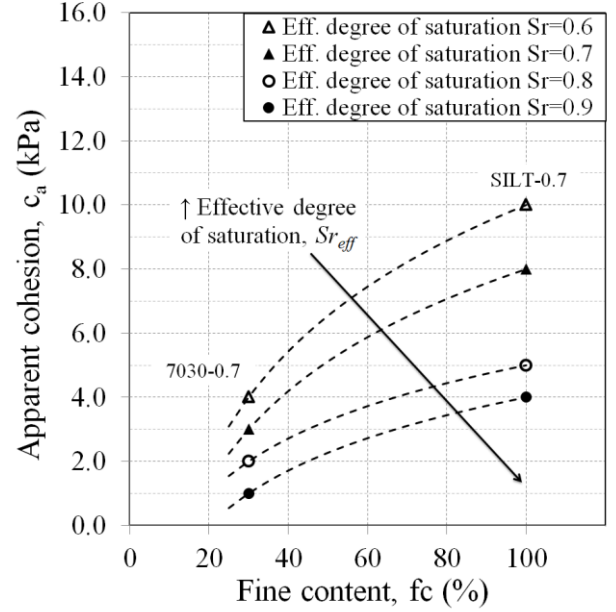


Figure 5. Influence of the fine content on the apparent cohesion for different effective degree of saturation levels.

The influence of the initial void ratio on the WRC of silty samples was studied by fitting the experimental points using the van Genuchten model (Figure 6).

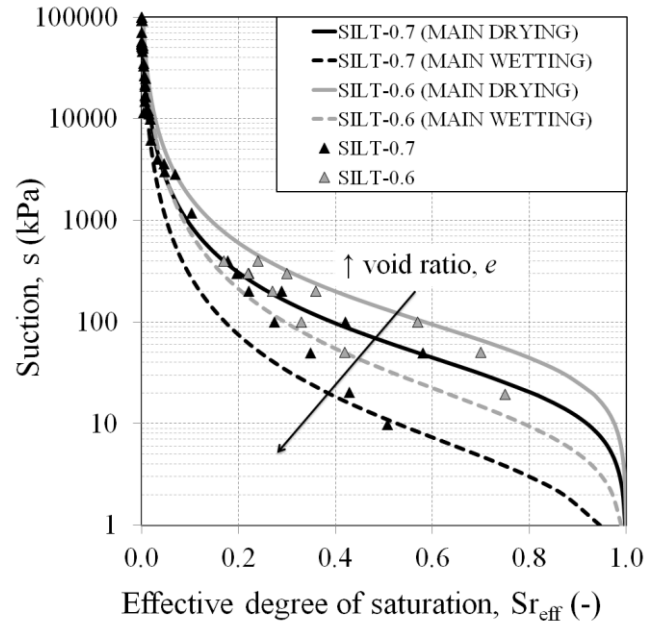


Figure 6. Influence of the initial void ratio on the WRC.

Both the main drying and wetting branches were influenced by initial void ratio of the samples. An increase in the void ratio moved the WRC to a lower suction because as the size of the pores increase, a lower suction was required to empty the pores. For this reason, the WRC of SILT-0.6 rested above the curve of SILT-0.7.

Figure 7 gives the main drying WRC at different compaction states for more standard soils (speswhite kaolin specimens), highlighting a good agreement with the experimental results obtained in this research on Stava tailing specimens at different void ratios. Within the suction range investigated for both cases, the Water Retention Curves were shifted upward with decreasing the initial void ratio of compacted soil.

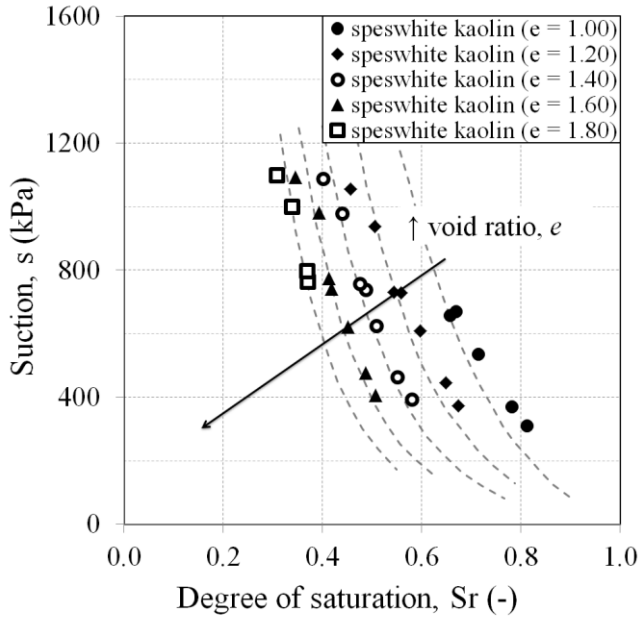


Figure 7. Water Retention Curves for speswhite kaolin specimens (modified from[12]).

The effect of the initial void ratio on the increase of the shear strength due to the unsaturated conditions was estimated from the WRC for different effective degree of saturation levels (Figure 8). The apparent cohesion decreased with the increase of the initial density, and it decreases with the increase of the effective degree of saturation. It can be observed that, within the most common expected in-situ densities, the unsaturated conditions allow to gain an apparent cohesion approx. equal to 10-20 kPa that will be completely lost as far the saturated conditions will occur.

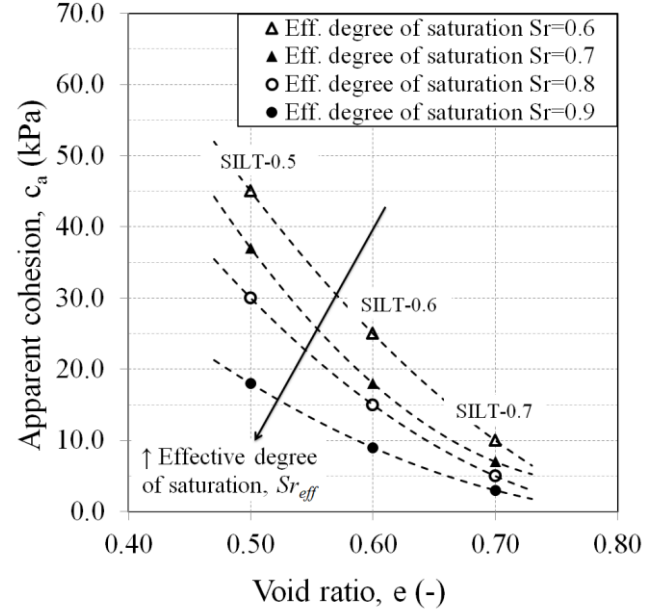


Figure 8. Influence of the void ratio on the apparent cohesion for different effective degree of saturation levels.

The influence of the void ratio on the relative hydraulic conductivity k_r (Figure 9) was estimated according to the model proposed by Muamel, 1976 ([13]):

$$k_r = S_{r_{eff}}^{1/2} \left[\left(\int_0^{S_{r_{eff}}} dx/s(x) \right) / \left(\int_0^1 dx/s(x) \right) \right]^2 \quad (3)$$

where dx is a dummy variable of integration ($dx=Sr_{eff}$).

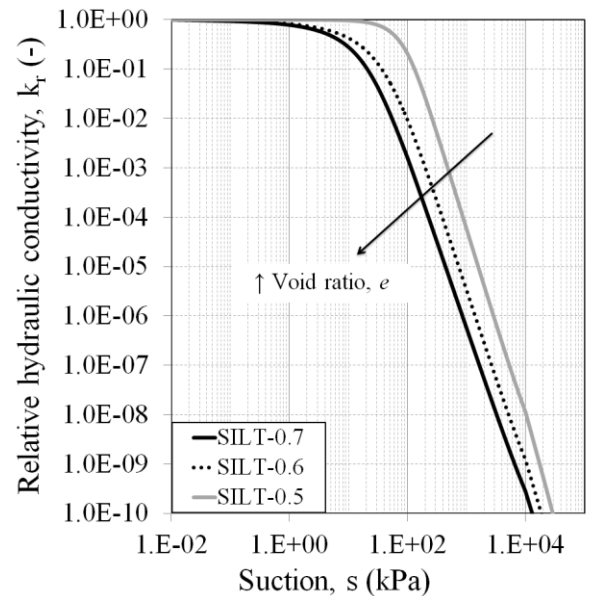


Figure 9. Influence of the void ratio on k_r .

The comparison between the relative permeability of pure silt samples (SILT-0.7, SILT-0.6, and SILT-0.5) prepared at different initial void ratio, shows that an increase of the initial density moves the relative hydraulic conductivity to lower suction range (Figure 9). It is worth to note that the relative permeability is obtained from the WRC, so at the same suction level denser sample SILT-0.5 exhibits a higher degree of saturation (and so a higher relative permeability) than looser sample SILT-0.7.

The effects of different initial densities and grading on the WRC can be also studied by assuming that the water retention is due to the capillary mechanism described by Washburn-Laplace equation:

$$r = \frac{2 \cdot T_s \cdot \cos(\alpha)}{s} \quad (4)$$

$$PSD = \Delta \left[\frac{e(1 - S_{r_{eff}})}{Gs} \right] / \Delta \log(r) \quad (5)$$

where α is the contact angle between water and pore's wall equal to 0° , T_s is the water tension equal to 72 Nm/m at temperature of 20°C). The cumulative value of the pore size density is represented in Figure 10.

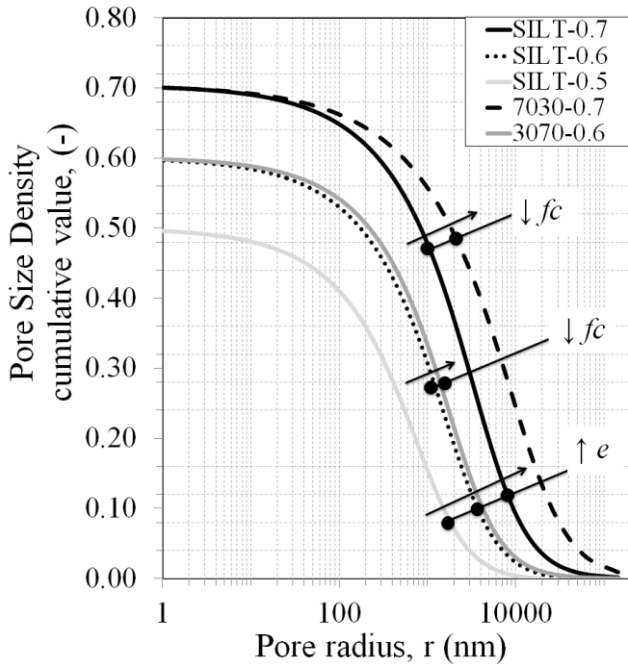


Figure 10. Cumulative value of the PSD for all tested samples.

A comparison of the effect of the initial void ratio in terms of cumulative PSD allows one to observe that

sample SILT-0.7 has a bigger cumulative curve than samples SILT-0.6 and SILT-0.5: this means that the first one has a higher number of large size pores that can be firstly intruded by water. A comparison of the effect of fine content in terms of cumulative PSD allows one to observe that, even if the two samples have the same initial cumulative value of the PSD (at $r = 1$ nm) due to their same initial void ratio ($e_i = 0.7$), cumulative PSD of sample 7030-0.7 is bigger than those of SILT-0.7. This means that the sample 7030-0.7 has a higher number of large size pores that can be firstly filled by water. Similar considerations could be made by comparing the cumulative PSD of sample SILT-0.6 with those of sample 3070-0.6.

5. Conclusion

This research has provided an insight into the effects of the initial density and fine content on the water retention behaviour of unsaturated Stava tailings. The reduction of void ratio was proved to shift the hydraulic response to a higher suction range because the size of the pores decreases. The experimental results were successfully compared with those described in literature on more standard soils. The water retention response of different sand-silt mixtures with the same initial void ratio were studied by analysing their WRC. A reduction of the fine content was proved to move the water retention to lower suction values as the big pores between sandy particles get emptied with silty particles, leading to a lower water retention capability of silt-sand mixtures than pure silt samples. Furthermore, because of coupling of the hydro-mechanical behaviour in unsaturated conditions, variations of the WRC due to changes in void ratio and fine content were proved to affect the apparent cohesion and the relative hydraulic conductivity of the samples. Finally, a microstructural interpretation of the water retention behaviour of Stava tailings was given in terms of pore size density. The experimental results find their practical application as relevant aspects for a reliable assessment of performances and stability of tailing dams.

6. Acknowledgement

The Author wishes to thank Prof. Guido Musso (Politecnico di Torino) for his valuable inputs, and Dr. A. Azizi, O. Pallara, G. Bianchi (Politecnico di Torino) for their help during the laboratory tests.

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