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Effects of low suction and wetting–drying cycles on filtered tailings shear strength

VH Le *Polytechnique Montréal, Canada*

T Pabst *Polytechnique Montréal, Canada*

Abstract

Filtered tailings management has many advantages over traditional slurry tailings management, such as improved water recovery and recirculation, and a reduction of geotechnical risk. However, the long-term evolution of the water content in filtered tailings exposed to climatic conditions could affect its geotechnical properties. Shear strength properties of unsaturated tailings have a critical role when evaluating the geotechnical stability of a dry stack facility, especially in the context of climate change. The objective of this research was, therefore to investigate the influence of drying and wetting cycles on the shear strength of filtered tailings for a low matric suction range (i.e. 0~50 kPa). A series of consolidated–drained (CD) direct shear tests were conducted on re-compacted unsaturated filtered tailings specimens. For each matric suction achieved by following either the wetting or drying curve, three direct shear tests were performed with varying normal stresses. Direct shear test results showed a nonlinear increase in the unsaturated shear strength with the normal stress and matric suction. Empirical hyperbolic functions were used to fit experimental data and evaluate the shear strength of unsaturated filtered tailings for a higher matric suction range. Test results also indicated some hysteresis, and the shear strength during drying was smaller than during wetting for the same matric suction. However, matric suction and water retention curve (WRC) hysteresis had no significant impact on the measured effective friction angle.

Keywords: *unsaturated filtered tailings, shear strength, matric suction, water retention curve, direct shear*

1 Introduction

One of the most challenging issues faced by the mining sector is the management and safe disposal of large amounts of mine wastes produced during operations (Berger 2017; Espinoza & Morris 2017; Yilmaz & Fall, 2017). The volume of mining waste stored in surface tailings storage facilities (TSFs) has constantly and significantly increased recently; therefore increasing risks associated with tailings dam stability (Azam & Li 2010; Ferdosi et al. 2015). Several tailings dam failures with catastrophic consequences for the local population and ecosystem (Morgenstern et al. 2015; 2016; Reid 2019; Robertson et al. 2019) have seriously harmed the image of the mining industry and highlighted the need for new tailings management approaches. Water management in TSFs is a recurrent cause of failure in most tailings dams, including elevated porewater pressures, hydraulic gradients and groundwater levels (East & Fernandez 2021).

In recent years, developments of tailings dewatering technologies, and especially filtered tailings, have contributed to maximise water recovery and minimise geotechnical risk (Simms 2017, 2021). The objectives of filtered tailings in particular are to produce tailings with solid content greater than 80% using various dehydration processes (Lara et al. 2013; Weatherwax & Kipara 2010). Filtration contributes to create an unsaturated cake that can be stored without requiring large slurry tailings ponds. Filtered TSFs are compacted and self-supporting structures with sloping sides instead of confining structures. Consequently, tailings filtration presents many advantages over traditional slurry tailings, including increased water recovery and recirculation, smaller footprint, reduced risk for slope instabilities, and enhanced social acceptability (Cacciuttolo et al. 2014; Caldwell & Crystal 2015; Copeland et al. 2006; Crystal et al. 2018; Qi & Fourie 2019).

The probability of failure in filtered TSFs is significantly reduced compared to conventional slurry TSF but the risk still exists (Wilson & Robertson 2015). Filtered TSFs are constructed on the surface and are exposed to climate conditions (Daliri et al. 2016; Simms, 2017, 2021). Global warming will contribute to increase the frequency of extreme weather events such as droughts and heavy rains with direct consequences on mining operations (O'Gorman 2015). Therefore, filtered tailings are (and will continue to be) exposed to repeated drying (due to evaporation) and wetting (due to precipitation) cycles (Fredlund & Houston, 2013; Fredlund 2019; Simms 2021). Understanding the hydro-mechanical responses of filtered tailings to wetting and drying cycles is therefore crucial to ensure the short- and long-term the stability of filtered TSFs (Cacciuttolo Vargas & Pérez Campomanes 2022).

This research aimed to characterise the hydro-mechanical behaviour of filtered tailings and the effects of the unsaturated conditions on their shear strength. The study was conducted by investigating tailings strength using one-dimensional consolidation and drained direct shear experiments on compacted filtered tailings at various degrees of saturation. More specifically, the objectives were to investigate the effect of the low suction and the wetting–drying hysteresis behaviour on filtered tailings shear strength and volume change behaviours, the effects of wetting–drying hysteresis on the relationship between the shear strength parameters and the suction, and the shear strength response of unsaturated filtered tailings to a large range of suctions.

2 Material and methodology

2.1 Tailings sampling and characterisation

Tailings were obtained from the Eleonore gold mine, located in the James Bay Region of Quebec, Canada. The D_{10} ranged between 0.0013 and 0.0045 mm, and the D_{60} ranged between 0.021 and 0.0032 mm (Figure 1). The corresponding coefficient of uniformity C_U (D_{60}/D_{10}) was between 8 and 18. The percentage of particles passing through the 2 and 80 µm meshes was between 2 and 12%, and 91 and 93%, respectively. Results were therefore similar to those observed in tailings sampled from Canadian hard rock mines (Bussiere 2007). The tested tailings contained more than 90% of non-plastic fines (particles smaller than 75 µm) and were classified as non-plastic silts with sand (ASTM International 2017).

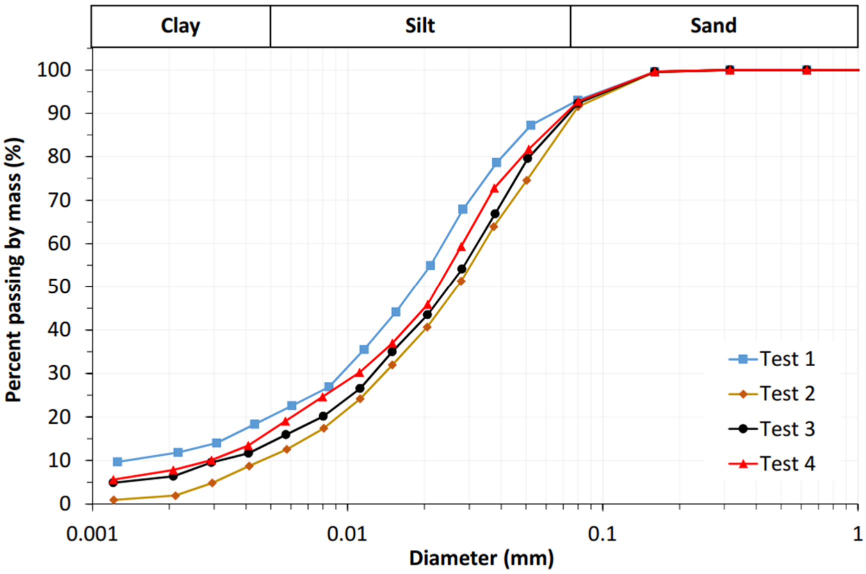


Figure 1 Particle size distribution curves of tested filtered tailings

2.2 Water retention curve and hysteresis

The drying path of the water retention curve (WRC) was simulated using a pressure plate (ASTM International 2016). Tailings specimens were compacted in 50 mm diameter and 20 mm high rings at an initial dry density of 1.7 g/cm^3, i.e. the initial void ratio of 0.6. Specimens were then saturated in a saturation chamber for more than 48 hours and weighed. Seven increments in suction were applied by adjusting the pressure regulators (i.e. 30, 45, 60, 90, 120, 175 and 300 kPa). After each suction increment, the specimen was taken out of the pressure plate and its final water content was determined by weighing to the nearest 0.001 g.

The wetting path of WRC was measured using a Temp cell (ASTM International 2016). The specimen size was 75 mm in diameter and 20 mm in height. The specimens were compacted completely dry and placed inside a sealed chamber on a saturated ceramic disk (air-entry value = 150 kPa). Air pressure was supplied at the top of the chamber and a constant water pressure of 20 kPa was maintained at the bottom of the ceramic disk using a hydraulic automatic pressure controller (APC) system. Seven suction increments (the same as for the drying curve) were applied and decreased gradually (i.e. 95, 75, 70, 65, 60, 55, 50 and 40 kPa). Equilibrium was considered reached when the water volume had not changed (i.e. < 0.001 mL) for at least 48h.

2.3 Unsaturated shear strength

A shear strength equation for an unsaturated tailings in which two independent stress state variables are used was proposed by Equation 1 (Fredlund et al. 1978):

$$\tau_f = c' + (\sigma - u_a)tan\phi' + (u_a - u_w)tan\phi^b \tag{1}$$

where:

τ_f = the shear stress on the failure plane at failure (kPa).

c' = the intercept of the extended Mohr–Columb failure envelope.

$(\sigma - u_a)$ = the effective normal stress (kPa).

ϕ' = the angle of internal friction associated with the effective normal stress.

$(u_a - u_w)$ = the matric suction (kPa).

ϕ^b = the friction angle associated with suction.

Equation 1 describes a planar surface representing tangent lines to the failure circles. The shear strength of unsaturated tailings is contributed to by an effective cohesion c' and the independent components including net normal stress $(\sigma - u_a)$ and suction value $(u_a - u_w)$. The shear strength components from effective net normal stress and matric suction are distinguished by ϕ' and ϕ^b angles, respectively. The failure envelope is the same as the Mohr–Coulomb failure envelope for saturated conditions.

Likewise, the shear strength of unsaturated tailings was proposed by a more general, nonlinear function using the entire water retention curve (i.e. 0 to 10000000 kPa) and the saturated shear strength parameters as shown in Equation 2 (Vanapalli et al. 1996):

$$\tau_f = c' + (\sigma - u_a)tan\phi' + (u_a - u_w)tan\phi' \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) \tag{2}$$

where θ_r, θ_s and θ are the residual, saturated and volumetric moisture content.

Unsaturated shear strength characteristics of filtered tailings were investigated through a series of constant suction consolidated–drained direct shear tests (DST) under low suction values (i.e. 0~50 kPa). Then, these proposed procedures in Equations 1 and 2 were used to evaluate the shear strength of unsaturated tailings in case a large range of matric suctions is considered. All the tests were performed on Eleonore filtered tailings with an initial dry density of 1.7 g/cm^3 and an initial gravimetric water content of 16%. A high air-entry ceramic disc with an air-entry value (AEV) of 150 kPa was equipped to control suctions by using the axis translation technique (Hilf 1956). The pore air pressure was applied and adjusted by an air automatic pressure controller (APC) inside a sealed box. The porewater pressure was also controlled using a hydraulic APC system which can record the water volume change of the specimen.

The testing procedure was based on DST of fine-grain soils under consolidated–drained conditions (ASTM International 2011). First, the ceramic disk with an AEV of 50 kPa was installed in the lower part of the shear box and was fully saturated inside a vacuum chamber with de-aired water until no gas bubbles were visible. The tailings were compacted and saturated in a saturated chamber. Once saturated, they were placed in the shear box. Air pressure was supplied through an inlet tube connected to the top of the chamber while water pressure was maintained at the target pressure using the hydraulic APC. The outlet tube located at the base of the samples allowed water to drain out from the specimens until equilibrium was reached.

The procedure of drying process was carried out for seven suction values (i.e. 0, 10, 25, 30, 35, 40, 45 and 50 kPa) (Table 1). Saturated tailings were placed in the closed direct shear box and the target air pressure and water pressure were applied (water pressure was maintained constant around 0 kPa during the entire drying process). The specimens were allowed to equilibrate until the recorded water volume in the hydraulic APC was not changed (<0.005 mL in 24 hours). Tailings were then consolidated at specified normal stress (e.g. 25, 50 and 100 kPa) while maintaining a constant air pressure and water pressure. Tailings were sheared with a shear displacement rate of 0.005 mm/min. Vertical and shear displacements were recorded every 10 seconds with a four-channel data logging system.

Table 1 Initial tailings properties before conducting DST the during drying process

Suction (kPa)	Initial condition			Water pressure (kPa)	Air pressure (kPa)	Normal stress, σ (kPa)	Net normal stress, $\sigma - u_a$ (kPa)
	Initial void ratio, e_i	Initial degree of saturation, S_{ri} (%)	Initial volumetric water content, θ_i				
10	0.614	100	0.380	0	10	35	25
	0.638		0.390			60	50
	0.632		0.387			110	100
25	0.616	100	0.381	0	25	50	25
	0.614		0.380			75	50
	0.616		0.381			125	100
30	0.623	100	0.384	0	30	55	25
	0.605		0.377			80	50
	0.616		0.381			130	100
35	0.606	100	0.377	0	35	60	25
	0.608		0.378			85	50
	0.613		0.380			135	100
40	0.610	100	0.379	0	40	75	25
	0.612		0.380			100	50
	0.611		0.379			150	100
50	0.606	100	0.377	0	50	75	25
	0.612		0.379			100	50
	0.605		0.377			150	100

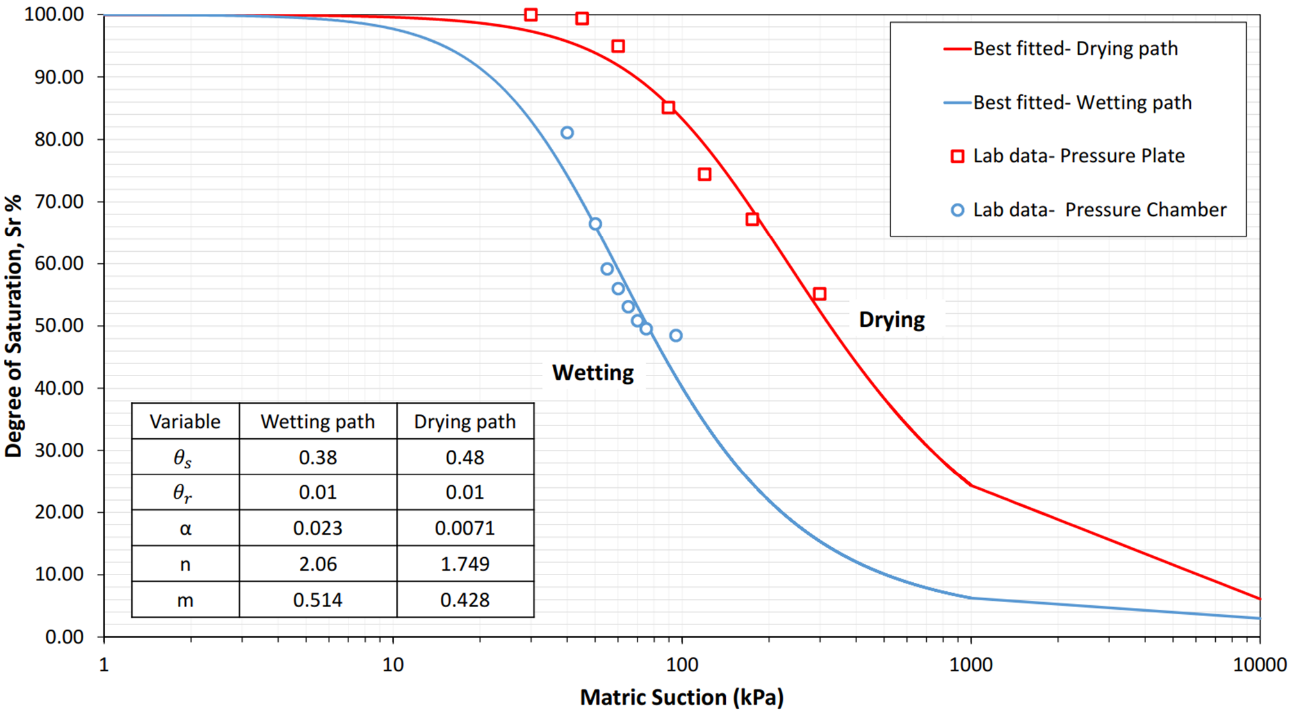
The procedure for wetting was also conducted for seven suction values (i.e. 0, 10, 25, 30, 35, 40, 45 and 50 kPa) (Table 2). Tailings were prepared with predetermined initial water content corresponding to each suction value based on the wetting WRC. Tailings were then re-compacted using a 20 mm high and 75 mm diameter retaining ring. Compacted tailings were then placed in the closed direct shear box when applying air pressure and water pressure. Equalisation in the specimens was achieved when the recorded water volume in the hydraulic APC did not change (<0.005 mL in 24 hours). The tailings were then consolidated at a specified normal stress (e.g. 25, 50 and 100 kPa) while maintaining the air pressure and water pressure constant. Tailings were sheared with a shear displacement rate of 0.005 mm/min. Vertical and shear displacements were recorded every 10 seconds with a four-channel data logging system. Reaching equilibrium required 1–3 days.

Table 2 Initial tailings properties before conducting DST following the wetting process

Suction (kPa)	Initial condition			Water pressure (kPa)	Air pressure (kPa)	Normal stress, σ (kPa)	Net normal stress, $\sigma - u_a$ (kPa)
	Initial void ratio, e_i	Initial degree of saturation, S_{ri} (%)	Initial volumetric water content, θ_i				
0	0.622	100	0.383	0	0	25	25
	0.604	100	0.377			50	50
	0.613	100	0.380			100	100
10	0.617	97.0	0.370	20	30	55	25
	0.627	95.4	0.368			80	50
	0.64	93.7	0.366			140	100
25	0.616	93.8	0.358	20	45	70	25
	0.614	93.3	0.355			95	50
	0.616	94.1	0.359			145	100
30	0.623	88.6	0.340	20	50	75	25
	0.605	87.6	0.330			100	50
	0.616	89.1	0.340			150	100
35	0.606	87.4	0.330	20	55	80	25
	0.608	87.4	0.330			105	50
	0.613	87.2	0.331			155	100
40	0.610	81.7	0.309	20	60	85	25
	0.612	81.8	0.310			110	50
	0.611	83.0	0.315			160	100
50	0.606	70.3	0.265	20	70	95	25
	0.612	68.6	0.260			125	50
	0.605	70.7	0.267			170	100

3 Results

Water retention curve data was interpreted using the model (van Genuchten, 1980) (Figure 2). Saturated volumetric water content (θ_s), residual volumetric water content (θ_r) and other parameters including α (kPa), n (–) and m (–) were fitted for both wetting and drying curves. The AEVs of the tested tailings for wetting and drying curve were 25 and 50 kPa, respectively.



Variable	Wetting path	Drying path
θ_s	0.38	0.48
θ_r	0.01	0.01
α	0.023	0.0071
n	2.06	1.749
m	0.514	0.428

Figure 2 Water retention wetting and drying curves

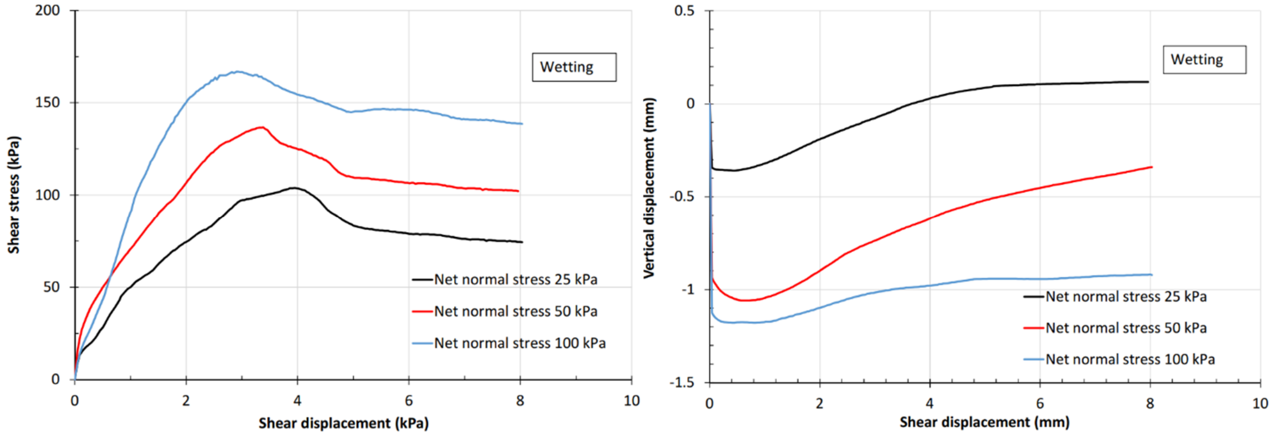
The shear strength of the saturated filtered tailings was obtained using direct shear box, with an effective cohesion (c') and effective friction angle (ϕ') of 18 kPa and 42.5°, respectively. The shear strength parameters of saturated tailings were then compared for a suction of 0 kPa.

3.1 Effects of net normal stress on filtered tailings shear strength and volume change

The shear strength and the initial stiffness of the unsaturated filtered tailings increased with increasing net normal stress($\sigma - u_a$). Under constant suction, increased vertical stress caused a progressive tailings volume change from contraction (i.e. negative vertical displacements) to dilation until dilatancy completely disappeared. Obviously, tailings became denser under increasing net normal stress; therefore, the shear resistance and the initial stiffness increased. Figures 3 and 4 indicate shear stress–shear displacement and volumetric behaviours of filtered tailings as a function of the net normal stress with constant suction of 25 kPa, which followed the wetting and dry process, respectively.

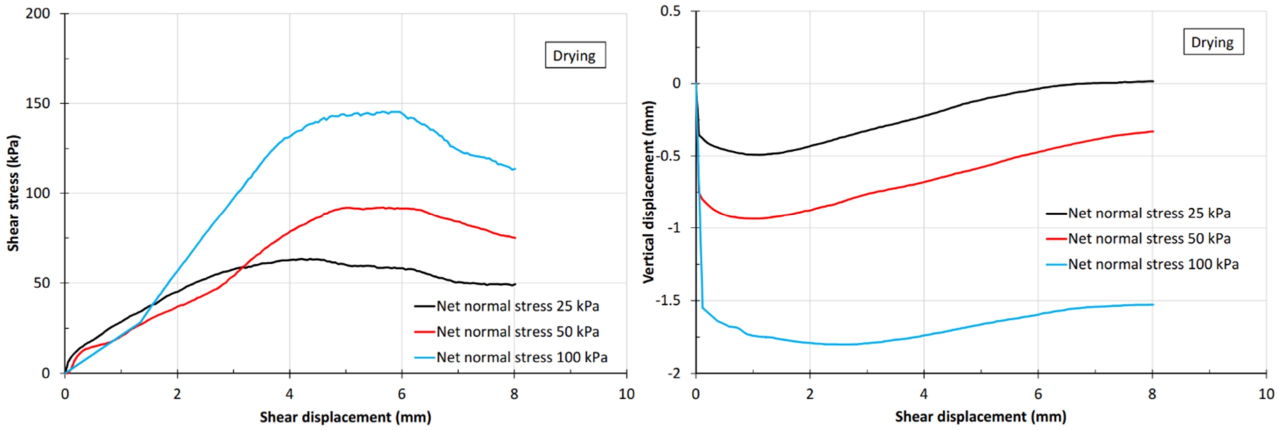
For example, greater vertical stresses induced higher peak shear stresses resulting in the increase in tailings shear strength. The observed peak shear stresses increased from 104 to 136 kPa and to 166 kPa under net normal stress of 25, 50 and 100 kPa for a suction of 25 kPa with the wetting process, respectively. A similar effect was observed for increasing net normal stress on tailings confinement, inducing the increase of tailings shear stiffness (i.e. the initial slope of the shear stress–shear displacement curve) with the vertical net normal stress (Figures 3a and 4a). For the same suction of 25 kPa (wetting path), the vertical displacements of filtered tailings decreased from -0.4 mm, to -1.1 mm and finally to -1.2mm, for an increasing net normal stress of 25, 50 and 100 kPa, respectively. Tests conducted on filtered tailings with a constant suction of zero (saturated samples), 10, 30, 35, 40 and 50 kPa by following either wetting or drying paths indicated similar results.

Moreover, the maximum negative vertical displacements of tailings for small net normal stresses (i.e. 25 and 50 kPa) following the wetting process were smaller than those obtained following the drying process. For example, the maximum negative vertical displacements of filtered tailings for a suction of 25 kPa (wetting path) were -0.36 mm, compared with -0.5 mm (drying path) for a net normal stress of 25 kPa. Instability risk of filtered tailings therefore seems higher for wetting than drying paths at small net normal stresses.



(a) (b)

Figure 3 **(a) Shear stress–shear displacement behaviour, and (b) volumetric behaviour of unsaturated filtered tailings (25 kPa suction following wetting process) as a function of the net normal stress**

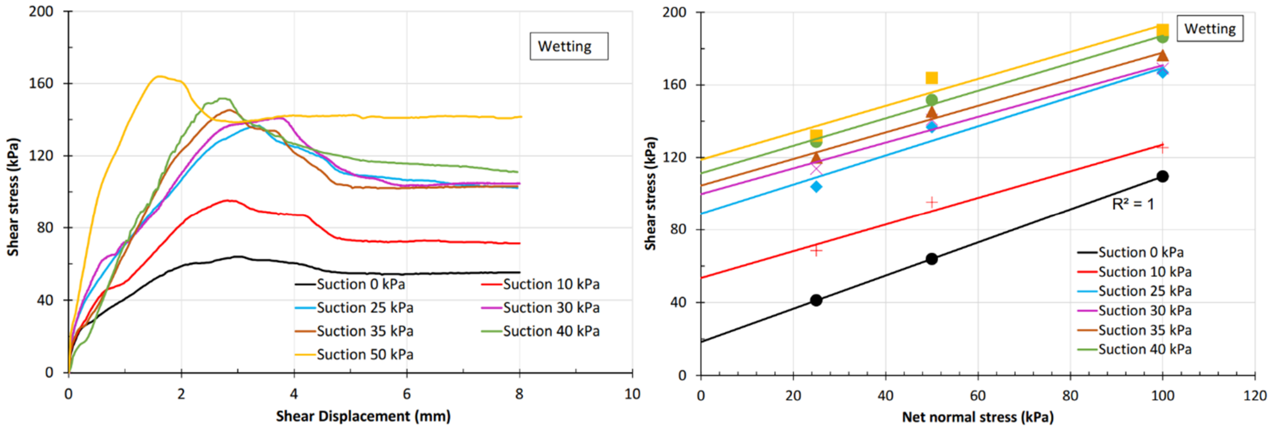


(a) (b)

Figure 4 **(a) Shear stress–shear displacement behaviour, and (b) volumetric behaviour of unsaturated filtered tailings (25 kPa suction following drying process) as a function of the net normal stress**

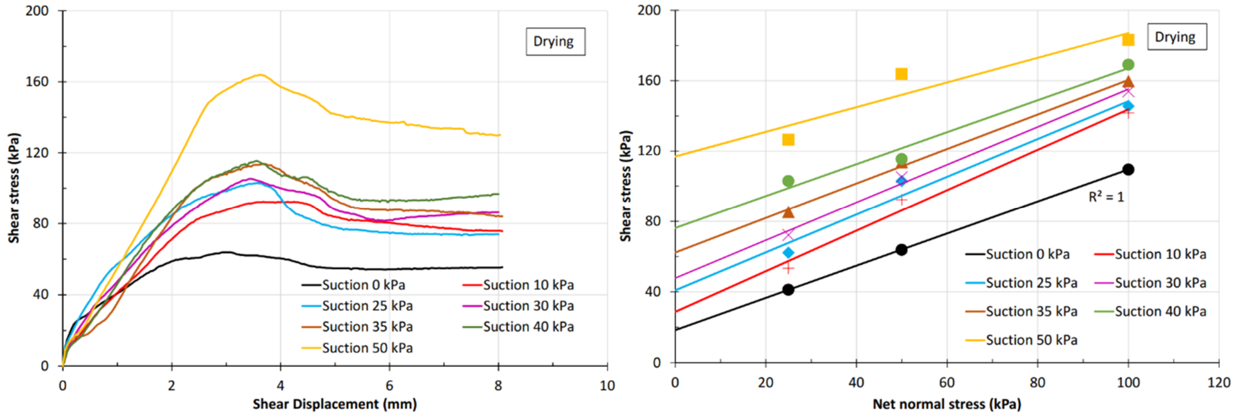
3.2 Effects of suction on filtered tailings shear strength

The tailings shear strength and shear strength envelope increased with the increase in suction. Figures 5 and 6 indicate shear stress–shear displacement behaviour for a constant net normal stress of 50 kPa and shear strength envelope of filtered tailings as a function of the suction, which followed the wetting and drying process, respectively. For the same net normal stress of 50 kPa, the peak shear stresses of filtered tailings increased from 64 to 95 to 137 to 141 to 145 to 152 and finally 164 kPa, for an increasing suction of 0, 10, 25, 30, 35, 40 and 50 kPa, respectively (Figures 6a and 6b). For failure envelopes under different suction values, the internal friction angle, ϕ', remains essentially constant. The tested filtered tailings results plotted regarding stress state variables following both the wetting and drying process (Figures 5b and 6b) show an almost linear relationship. Therefore, the failure surface of the tested filtered tailings was considered planer and the Mohr–Coulomb criterion (i.e. Equation 1) was used to evaluate the shear strength of unsaturated filtered tailings.



(a) (b)

Figure 5 (a) Shear stress–shear displacement behaviour for a constant net normal stress of 50 kPa; (b) Shear strength envelopes of unsaturated filtered tailings (wetting path) as a function of suction



(a) (b)

Figure 6 (a) Shear stress–shear displacement behaviour for constant net normal stress of 50 kPa; (b) Shear strength envelops of unsaturated filtered tailings (drying path) as a function of suction

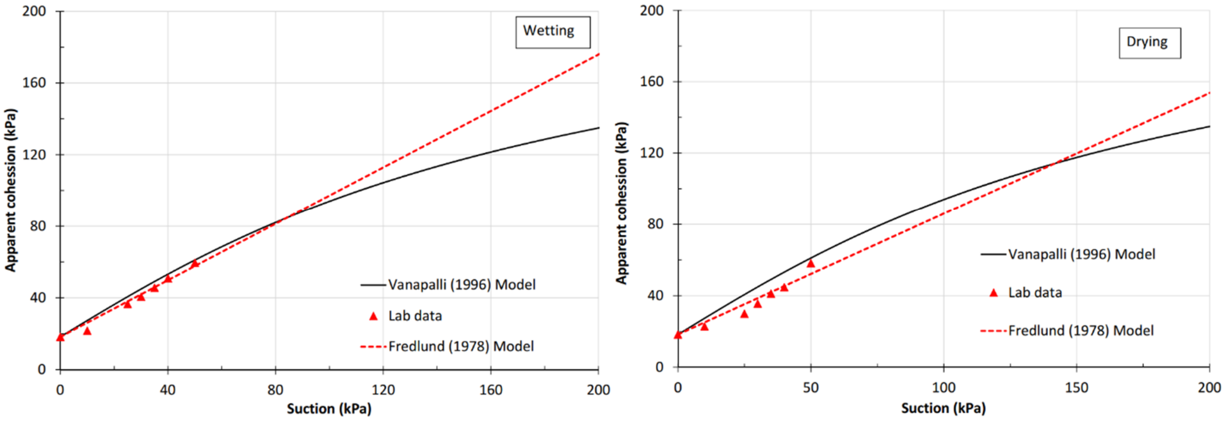
3.3 Suction strength as a function of matric suction

The contribution of suction and the friction angle associated with decreasing suction to the shear strength of the tested tailings decreased much faster in the case of wetting path compared to drying path. For example, the friction angles of filtered tailings (wetting path) decreased from 39 to 38 to 37 to 36 and finally to 19° for a decreasing suction of 50 to 40 to 35 to 30 to 25 and finally to 10 kPa, respectively. Meanwhile, the values (for drying path) decreased from 39 to 33 to 30 to 25 and finally to 24° for the same decreasing suction. The contribution of suction and friction angle associated with suction to the shear strength envelope of filtered tailings was smaller for the wetting path than for the drying path. Instability risk therefore seemed greater for wetting than for drying for low suction around a saturated state.

Table 3 shows the tendency of change in the friction angle associated with suction, ϕ^b. The red line shows the linear contribution of suction and friction angle associated with suction to the shear strength envelope. Figure 7 indicates the contribution of suction and friction angle associated with suction to the apparent cohesion of filtered tailings. The average value of ϕ^b was found to be about 38° for the wetting process and 34° for the drying process. The results from all consolidated–drained DSTs with filtered tailings indicated that the angle ϕ^b is smaller than the internal friction angle,ϕ', for low suction values.

Table 3 **Data from tested filtered tailings specimens**

Wetting branch						
$u_a - u_w$ (kPa)	10	25	30	35	40	50
θ (%)	0.375	0.361	0.348	0.331	0.312	0.27
ϕ^b_{avg} (°)	19	36	37	38	39	39
Drying branch						
$u_a - u_w$ (kPa)	10	25	30	35	40	50
θ (%)	0.375	0.374	0.373	0.372	0.37	0.364
ϕ^b_{avg}(°)	24	25	30	33	33	39



(a) (b)

Figure 7 **Contribution of suction to the shear strength envelope of filtered tailings following (a) wetting conditions, and (b) drying conditions**

4 Discussion

The mechanical behaviour of unsaturated filtered tailings under low suction (0~50 kPa) and low net normal stress was investigated by DST. A series of shear tests was performed on tailings (both drying and wetting paths) under various combinations of suction and net normal stress to evaluate the effect of wetting and drying (the hysteresis of WRC) on the shear behaviour of filtered tailings. The results of the experimental study are summarised as:

- Net normal stress had a direct influence on the shear strength and volume change of unsaturated filtered tailings following both the wetting and drying paths. An increase in net normal stress increased the shear strength of filtered tailings and decreased the volume change.
- The shear strength of filtered tailings also increased with the suction. For suction, shear strength was more marked during wetting than drying.
- The effective friction angle of filtered tailings obtained from consolidated–drained (CD) direct shear tests seemed to be independent of suction and of WRC hysteresis. Consequently, the effective friction angle ϕ' measured using saturated CD tests could also be used to evaluate the shear strength of unsaturated tailings for both the wetting and drying paths.
- The relation between shear strength and suction regarding the ϕ^b angle for both the wetting and drying paths was linear. A planar failure envelope can therefore be used to estimate the shear strength of filtered tailings at a higher range of suction.

- The shear strength of unsaturated filtered tailings was more affected by the changes of net normal stress than by the changes in suction. The risk for shallow instability on filtered TSF could therefore be much more significant during wetting than drying.

The results of this study will be used to evaluate the stability of filtered TSF under climatic conditions.

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