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Validating new simple shear tests on a partially saturated pyroclastic soil

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ABSTRACT: The paper presents a series of tests performed on remoulded specimens of a pyroclastic soil of Southern Italy, characterized by a metastable structure and prone to static liquefaction upon shearing. The tests were performed through the new Suction-Controlled Simple Shear apparatus (SCSS) of the University of Salerno (Italy). The device was designed to investigate the mechanical behaviour of unsaturated specimens and allow performing simple shear tests at Constant normal Load (CL) or at Constant Volume (CV). The results of new simple shear tests were discussed and a unique failure envelope for saturated and unsaturated specimens was opportunely obtained in the τ, σ' plane referring to a Bishop effective stress framework. The results were also well matched with more conventional triaxial tests and direct shear tests providing an overall validation of the new simple shear tests in terms of both friction angle and intercept cohesion.

1 INTRODUCTION

The shear strength of soils is an important parameter for geotechnical engineering practice and research. For instance, effective friction angle (φ') and intercept cohesion (*c*') generally serve as input data for landslides triggering analysis. The shear strength is usually obtained through triaxial (TX) or direct shear (DS) tests, for which the experimental results can be univocally elaborated.

However, in many geotechnical contexts, the loads imposed to the soil can be better approximated through Simple Shear apparatus (SS). The simple shear test closely approximates strain-stress paths for which the principal (stress/strain) axes are free to rotate, such as for slopes subjected to rainfall during the failure and post-failure mechanisms (Cuomo et al. 2015, 2016, 2017; Moscariello 2017). Although SS is suitable to apply realistic loading condition, it is less adopted than TX and DS. The interpretation of the experimental results of the simple shear tests can be done through different methods suggested in the literature to define the intermediate principal stress, which is unknown without elaborate instrumentation. A review of some methods and relative application is proposed in Cuomo et al. (2015).

The simple shear test can be carried out at Constant normal Load (CL) or at Constant Volume (CV) in k_0-conditions. The zero lateral strain conditions were originally accomplished through hinged metallic walls (in the Cambridge device; Roscoe 1953), or cylindrical wire-reinforced rubber membrane (NGI device; Bjerrum & Landva 1966). In both the configurations, only CV tests were possible. Other simple shear devices capable to perform truly undrained tests were designed afterwards (Casagrande 1976; Dyvik et al. 1978; Franke et al. 1979; Ishihara & Yamazaki, 1980; Silver et al. 1980; Tatsuoka & Silver, 1981).

Recent developments extended the potential of simple shear to partially saturated soils, which are common in nature, particularly in arid and semi-arid regions (Fredlund & Rahardjo 1993; Delage et al. 2008). Rahnenma et al. (2003) used the axis translation technique to control/measure the suction of cylindrical specimen in a special triaxial cell, equipped with a double-wall, capable to perform simple shear tests. Tombolato et al. (2008) presented a new simple shear device working on cuboidal specimen at constant degree of saturation and at constant volume. Sorbino et al. (2011) showed the potential of simple shear tests to characterise the hydro-mechanical response of partially saturated silty soils upon shearing. Similarly, Milatz and Grabe (2015) investigated the hydraulic-mechanical coupling of coarse-grained soils during monotonous and cyclic shear. Cuomo et al. (2016, 2017) and Moscariello (2017) recently performed simple shear tests on saturated and unsaturated specimens. Those former tests were carried out both at constant load and constant volume at different suction values on remoulded specimens of a non-plastic ashy soil. The strength mobilized in saturated condition in the simple shear device was compared to those relative to direct shear and triaxial devices. The differences were evaluated in terms of friction angle (ϕ) and the stress ratio at critical state (M). Moreover, the mechanical behaviour of soil upon wetting was also investigated through wetting test in simple shear condition (Cuomo et al. 2017). The time evolutions of shear stress, effective vertical stress, measured suction, shear strain and volume of water exchanged were analysed upon wetting (Cuomo et al. 2017).

In this paper, the shear strength envelope was obtained through simple shear tests performed in strain-controlled or in load-controlled conditions. The effect of stress/strain conditions on the mobilized shear strength was discussed. The results in terms of effective friction angle and intercept cohesion were compared with the data available in literature from TX and DS both on saturated and unsaturated specimens. To this aim, a very well documented soil was selected, and validation of the new simple shear tests was pursued by comparing the achieved results with those previously obtained. The shear strength was used to analyse the mechanical behaviour of remoulded pyroclastic soil upon wetting in simple shear condition at constant volume.

2 MATERIALS AND METHODS

2.1 *The soil tested*

The material investigated is a pyroclastic (air-fall volcanic) soil, produced by the explosive activity of Vesuvius volcano (Fig. 1). This soil was formerly studied by Bilotta et al. (2005) and classified as “class A ashy soil”. The tested soil is very porous (n = 0.66), light, non-plastic silt with sand (42% Sand, 50% Silt and 8% Clay), which is partially saturated in the field, during most of the seasons. The soil specific gravity (G_s) is 2.45; the saturation degree (S_r) is comprised between 79.6% and 99.3% (Migliaro 2008); the dry unit weight (γ_d) is 8.41 and 8.85 KN/m^3. The average water content (w) is 51.9%, while the liquid limit (w_L) is 53.8% and the plastic limit (w_P) is 49.3%. Richard’s pressure plate and Volumetric extractor tests provided Soil Water Retention Curves, well interpolated through Van Genuchten (1980), with parameters equal to: S_{rs}= 0.94, S_{rr}= 0.46, α= 0.01, n=1.23 for drying and S_{rs}= 0.44, S_{rr}= 0.31, α= 0.50, n=1.24 for wetting.

The shear strength was analysed in previous contributions (Bilotta et al. 2005, 2008; Migliaro 2008) for undisturbed or remoulded specimens through saturated and suction-controlled triaxial apparatus and direct shear. The strength parameters of saturated remoulded soils, obtained through TX tests by Bilotta et al. (2005), were c'=12.6 kPa and φ'=35.9°, while at suction equal to 50 kPa, the intercept cohesion was 48.9 kPa and φ'=35.5°.

Figure 1. Excavation outcrop at the toe of Pizzo d’Alvano massif in pyroclastic deposits originated from Vesuvius volcano.

Matric suction produces a significant increment of the shear strength of both undisturbed and remoulded soils, more evident for remoulded specimens probably due to their different internal structure (Bilotta et al., 2005; Sorbino & Nicotera, 2013). DS shear tests performed at constant water content and in saturated conditions were performed (Bilotta et al. 2005 and 2008) and confirmed the significant increment of shear stress due to the increase of matric suction. Here, the specimens were remoulded and obtained mixing the dry soil, with distilled water to prepare slurry with water content equal to 1.5 times the liquid limit (w_L). The slurry was loaded under a vertical stress equal to 10 kPa in a 25 cm large, 10 cm high oedometer. One week sufficed for consolidation. The soil left to dry in the atmosphere for one day reduced its degree of saturation from 100% to about 80%.

2.2 *Simple Shear device for partially saturated soils*

The Suction-Controlled Simple Shear (SCSS) Device herein described (Fig. 2) allows applying a vertical load to a soil specimen, and a “shearing mode” through the application of a controlled (i) horizontal force or (ii) horizontal displacement.

A peculiarity is the shearing box made of a stack

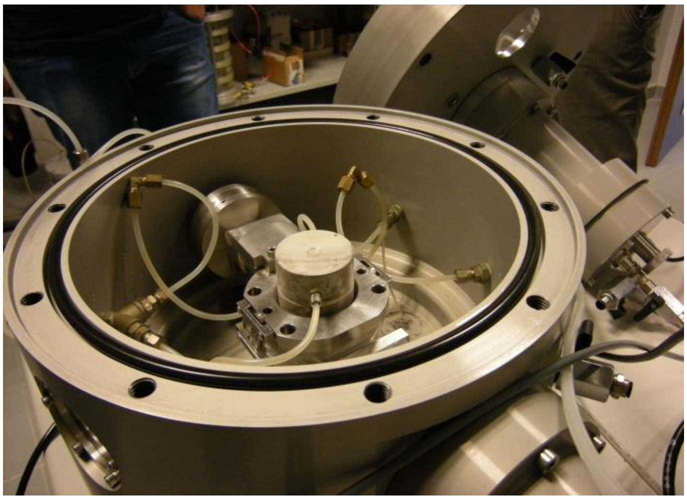

Figure 2. Picture of the inner part of the Suction-controlled Simple Shear apparatus (SCSS).

of twelve hollow disks which ensure zero lateral strain to the specimen. The disks are held together by two vertical screws doing the specimen assembly and removed before starting the shearing stage of the tests. The specimen housing has a circular inner cross section with a diameter equal to 51 mm. Cylindrical specimens 22 mm high are used. The specimen is sheared due to synchronized movement of two external double pendulum, fixed on bottom and top disks. Each of 12 disks is displaced along the shear direction using a small pivot (machined on the upper side of each disk), which can move only inside a linear fluting groove (machined on the lower side of each disk).

Matric suction is measured or applied using the axis-translation-technique through the independent control of pore air pressure and pore water pressure. Both the pressures are measured using two transducers with 0.1 kPa resolution.

Being both vertical load, shearing deformation and soil suction applicable to soil specimen, the SS is suitable to reproduce the in-situ conditions of a slope and the strain and stress paths induced by rainfall during the failure and post-failure mechanisms. The improvements of this new testing device if compared with the existing others are: i) control of matric suction or water content upon simple shearing; ii) specimen volume variations prevented or allowed (as for the tests herein reported) under stress- or strain- control; iii) smooth and continuous transition from partially- to fully-saturated condition upon wetting; iv) monitoring of hydro-mechanical response upon wetting, with both simple shearing and void ratio variations allowed.

2.3 *Testing programme*

All the tested specimens were firstly consolidated in k_0-conditions; then, the shearing of the specimen was performed at Constant Volume (CV).

Table 1. Initial conditions of simple shear tests performed at Constant vertical Load (CL) or at Constant Volume (CL).

	Test type^	e (-)	Sr (-)	s_b (kPa)	s_t (kPa)	σ' (kPa)	σ-u_a (kPa)
SSRPSF03a^^	CV	1.6	0.7	40.2	41.6	120.1	95
SSRPSF03b^^	CV	1.6	0.9	52.7	24.5	138.6	95
SSRPSG23	CL	1.6	0.9	25.1	23.7	71.7	50
SSRPSG24	CL	1.6	0.9	25.7	26.3	118.9	100
SSRPSG20	WCV	1.4	0.8	28.5	28.8	58.1	30
SSP0115*	CL	1.9	1.0	0.0	1.2	100.3	100
SSP0215*	CV	1.9	1.0	0.0	0.9	69.0	69
SSP0315*	CL	1.9	1.0	-0.1	-0.1	74.3	74

^ CL = Constant vertical Load, CV = constant Volume, WCV= wetting at constant Volume, ^^multistage test, * from Cuomo et al. (2016); s_b and s_t: suction values at bottom and top specimen; σ' vertical Bishop effective stress; σ-u_a net vertical stress.

The CV tests were performed controlling the vertical stress so that to inhibit the volume variation for the specimen. One multistage test was performed (marked with ^^ in Table 1), and they consisted in changing the stress path during a test on a single specimen. This type of test was selected in order to maximize the amount of shear strength information obtainable from one specimen. The SSRPSF03 was performed at constant volume, the first stage was carried out at nil suction, after that the second stage was performed at suction 20 kPa.

A wetting test at constant volume (SSRPSG20) was performed shearing and wetting the specimen at Constant Volume. The testing procedure consisted in the following steps: 1) measurement of the initial suction; 2) application of a suction and suction equalization; 3) application of a net vertical stress (30 kPa); 4) increase of the shear stress at constant height and water content, and suction equalization; 5) decrease of soil suction up to nil with rate -1.0 kPa/h, while the height and the shear stress (τ=34 kPa) were kept constant.

The tests were interpreted in terms of shear stress and the vertical effective stress as defined by Bishop (1959), referring to the "effective saturation degree" (S_{re}) as follows:

$$\boldsymbol{\sigma}'_{ij} = \boldsymbol{\sigma}_{ij} - u_a \cdot \boldsymbol{\delta}_{ij} + S_{re} \cdot (u_a - u_w) \cdot \boldsymbol{\delta}_{ij} \qquad (1)$$

where, $\boldsymbol{\sigma}_{ij}$ is the total stress tensor; u_a is the pore air pressure; u_w is the pore water pressure; u_a - u_w is the matric suction (s); $S_{re} = (S_r - S_{ro})/(1 - S_{r0})$; S_{r0} is the residual saturation degree here assumed equal to 0.31 and $\boldsymbol{\delta}_{ij}$ is the Kronecker delta.

3 RESULTS AND DISCUSSION

3.1 *CV and CL tests*

The tests performed at constant volume exhibited two different behaviours (Fig. 3): i) the SSRPSF03b test exhibited hardening behaviour; ii) the SSRPSF03a reached the maximum shear stress (80.77 kPa) at shear strain 0.07; the shear stress was then constant for shear strain reaching 0.2 and τ decreased to 72.44 kPa at $\gamma = 0.66$.

Although the three specimens were consolidated at three different effective stresses, during the constant-volume (CV) shearing stage, σ' showed an asymptote of about 60 kPa at large shear strain (Fig. 3). Two simple shear tests (SSRPSG23 and SSRPSG24) at constant vertical load were performed at net vertical stress of 50 kPa and 100 kPa and suction 25 kPa. Both tests exhibited dilative volumetric behaviour (Fig. 4b). The tests were then compared with some simple shear tests performed for saturated specimens at CV or Constant vertical Load (CL) conditions reported by Cuomo et al. (2015) and indicated with * in Table 1. The SSP0215 test exhibited a reduction of σ' at low deformation ($\gamma < 0.05$), while at larger deformation σ' increased and reached the maximum value equal to 60 kPa. The shear strain grew up monotony (Fig. 4). The specimens sheared at constant vertical load showed a slight hardening (Fig. 4a), associated to dilative behaviour (Fig. 4b).

The difference $|s_b - s_t|$ (i.e. difference of matric suction at the top and bottom boundaries of the specimen) was less than 4 kPa for all specimens sheared at constant vertical load (Tab. 2).

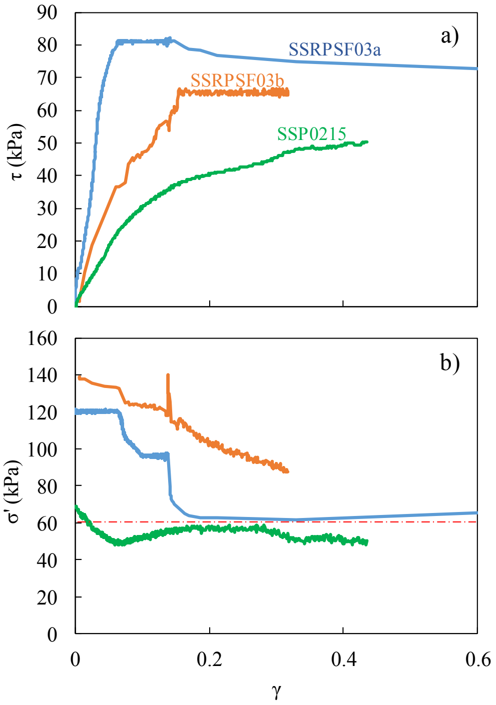

Figure 3. Results of Constant Volume (CV) simple shear tests performed on saturated and unsaturated specimens. The dashed line represents the asymptotic σ' reached at large shear strain.

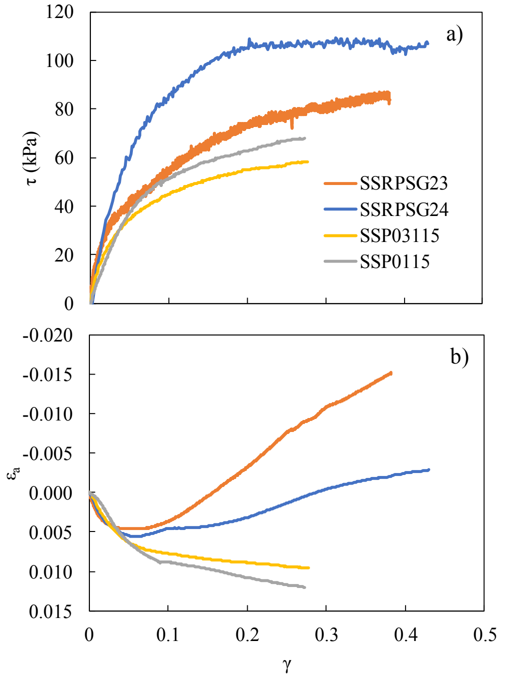

Figure 4. Results of simple shear tests performed at Constant vertical Load (CL) on saturated and unsaturated specimens.

Thus, the horizontal displacement rate and the shear stress rate were low enough to not induce excess pore water pressure for both saturated and partially saturated specimens. The shear strength envelope was obtained in terms of vertical Bishop effective stress thus, the data of both saturated and unsaturated specimens were adopted to obtain the effective friction angle and the intercept cohesion in the τ-σ' plane. The results of CL and CV tests were interpreted adopting $\varphi' = 35.8°$ and $c = 13.25$ kPa. The shear strength evaluated in terms of φ' and c can be compared to those achieved through triaxial and direct shear apparatus. As mentioned in Section 2.1, in literature the shear strength envelope was already available from TX and DS tests. Figure 5 compares the failure envelopes obtained from the TX, DS and SS tests in the τ-σ' plane. The whole set of results was interpolated with $\varphi' = 37.4°$ and $c = 7.32$ kPa.

Table 2. Stress variables (σ', τ), and differences between suction applied (s_b), and suction measured (s_t) at failure.

Test type^		σ' (kPa)	τ (kPa)	s_b (kPa)	s_t (kPa)	$s_t - s_b$ (kPa)
CL	SSP0115*	97.2	68.0	0.3	1.8	1.5
	SSP0315*	75.6	58.3	-0.3	1.4	1.7
	SSRPSG23	71.6	80.8	25.1	25.9	0.8
	SSRPSG24	120.0	108.7	24.6	26.9	2.4
CV	SSRPSF03a	114.1	81.3	25.0	29.7	4.8
	SSRPSF03b	87.9	66.1	14.7	14.3	-0.4
	SSP0215*	50.5	50.4	-0.4	2.1	2.6

^ CL = Simple Shear test performed at Constant vertical Load; CV = Simple Shear test performed in Constant Volume conditions; the tests marked with * are already discussed in Cuomo et al. (2016); s_b and s_t are the suction values at the bottom and top of specimen, respectively

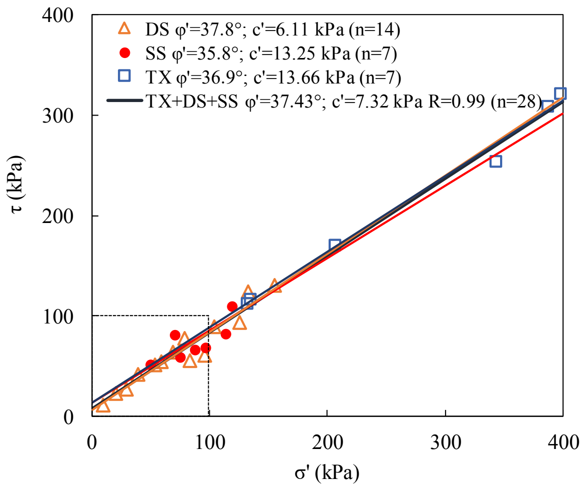

Figure 5. Shear strength envelope achieved through Simple Shear tests (SS; red line), Direct Shear tests (DS; orange line) and Triaxial tests (TX; blue line) on saturated and unsaturated specimens (data of TX and DS are taken from Bilotta et al., 2005 and 2008). The black line is the failure envelope obtained interpolating results of TX, DS and SS tests.

The friction angle and intercept cohesion achieved through triaxial tests for saturated and unsaturated specimens were φ'= 36.3° and c=13.66 kPa. The envelope obtained through direct shear tests has higher friction angle (37.8°), but lower intercept cohesion (6.11 kPa) than TX. The simple shear tests exhibited the lowest friction angle (35.8°). The moderate differences among the shear strength apparatus cannot be attributed only to the non-uniformity of stress and strain in simple shear tests because they also exist in triaxial and direct shear apparatus. The different stress condition imposed to the specimens by the three different devices play a role. However, the comparison matches recent similar outcomes made for saturated specimens by Cuomo et al. (2015).

3.2 *WCV tests*

The shearing (SHE) and wetting (WE) stages of SSRPSG20 test were performed at constant volume (Fig. 6). During the SHE stage, the volume and water content were kept constant. At the end of shearing stage, the shear strain was lower than 5%, while the degree of saturation exhibited low variation (from 0.82 to 0.84) and the net and effective vertical stress were still constant (30 kPa and 52.33 kPa respectively).

After shearing, the specimen was equalized at constant volume and at constant water content, thus the suction increased from 30 kPa to 38.6 kPa. Then, the specimen was wetted with a suction rate of -1.0 kPa/h. During the equalization stage (EQU), the net vertical stress was constant (30 kPa), the shear strain did not exhibit any variation, while the effective vertical stress σ' increased (up to 60 kPa). Upon wetting from suction 38.6 kPa to 8.0 kPa, the net vertical stress increased with rate $3.4 \cdot 10^{-1}$ kPa/s, while σ' decreased with an average rate of to $-1.56 \cdot 10^{-4}$ kPa/s. Then, for suction lower than 8.0 kPa, net and effective vertical stresses rapidly decreased.

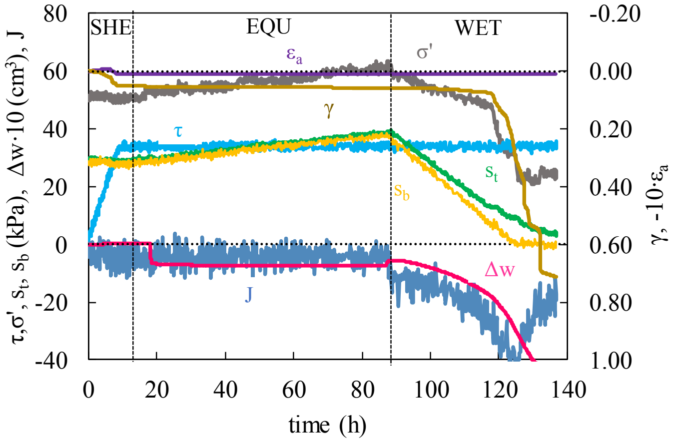

Figure 6. Stress (τ, s_t, s_b,) and strain variables (ε_a, γ) measured, and quantities computed (σ', Δw) for the shearing (SHE) and equalization (EQU) and (WET) stages of the test SSRPSG20.

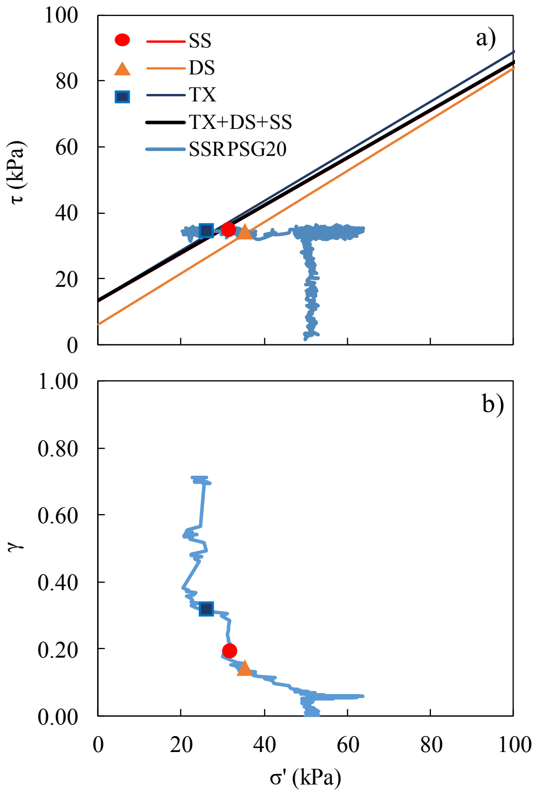

Figure 7. a) Stress path (τ, σ') and b) shear strain (γ) versus effective stress (σ') for the test SSRPSG20. The markers represent the intersection between the test results and the shear strength envelopes (square with TX envelope, triangle with DS envelope and circle with SS envelope).

Thus, the specimen exhibited the tendency towards contractive behaviour, which was observed through the progressive decrease of net vertical stress. The cumulative amount of water exchanged by the specimen (Δ*w*) was also measured, its time derivative represents the water flux, and was defined positive for an outflow from the specimen. The *Δw* was negligible upon shearing stage (SHE).

Upon wetting (WET) the water inflow trend was influenced by suction rate. Upon shearing and wetting, it was calculated the hydraulic gradient (*J*) from the suction values acquired both at the bottom (s_b) and at the top (s_t) of the specimens, thus defined positive for a downwards flux. The hydraulic gradient was almost constant upon shearing and equalization stages, while *J* decreased rapidly upon wetting.

Figure 7a indicates the intersection points between the shear strength envelopes (TX, DS, and SS) and the results of test SSRPSG20. The largest shear strain developed when the specimen reached the failure envelope obtained by TX tests (Fig. 7b).

4 CONCLUSIONS

Simple Shear (SS) tests were performed to investigate the mechanical behaviour of a remoulded partially saturated pyroclastic soil. The tests were carried out at Constant vertical Load (CL) or Constant Volume (CV) both in saturated and unsaturated conditions. The shear envelope was obtained combining results of CV+CL tests. The result was then compared to the shear envelopes achieved through TX and DS tests from literature and to the failure envelope obtained from the whole set of tests (TX, DS and SS).

The comparison between the shear strength parameters obtained through SS, TX and DS tests well matches those previously observed for saturated specimens, even if the effect of intercept cohesion was neglected in previous studies. The envelope of TX, DS and SS results exhibited friction angle and intercept cohesion close to the envelope of SS tests. However, this issue requires further experimental and theoretical investigation to fully understand and characterize the failure mechanism occurring in the simple shear device, compared to those relative to direct shear and triaxial devices.

The mechanical behaviour of soil upon wetting was also discussed with reference to a wetting test at constant volume in simple shear condition. The time evolution of suction, shear and axial strains and water exchange were measured. The specimen exhibited a dilatative behaviour upon wetting from suction of 30 kPa to 8 kPa and a contractive behaviour from 8kPa to null suction, with large shear strain. The evolution in the (τ, σ') and (γ, σ') planes was analysed and compared with the three failure envelopes obtained through three different devices, which applied three different stress/strain conditions. Further tests will be necessary to investigate different stress ratios and different rates of shear strain and suction reduction during the wetting stage.

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