# Water retention behaviour of compacted and reconstituted scaly clays

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**Abstract.** The paper presents the results of an experimental research devoted to investigate the response to suction variations of a scaly clay in compacted and reconstituted conditions. Different experimental techniques (axis translation, vapour equilibrium, dew point psychrometer suction measurements) were combined in order to explore the water retention properties in a wide suction range (0 ÷ 110 MPa). Experimental results allowed to define the water retention domains for a constant reference void ratio, highlighting the significant role of the microstructure on the response of the investigated clays. In particular, the collected results showed that in the low-medium suction range, the peculiar microstructural features give to the reconstituted clay a better retention capability than the compacted clay. However, the increasing suction induces a significative volumetric shrinkage on the saturated reconstituted clay, especially when the latter is initially normally consolidated. On the other hand, quite similar retention properties were recognized in the high suction range.

## 1 Introduction

The response to the boundary hydraulic condition variations, deriving for example from changes in climatic and environmental conditions, is a fundamental understanding for the analysis of the behaviour of unsaturated soils. The mechanical response, both in terms of the shear strength and volumetric behaviour, of unsaturated geomaterials is deeply affected by the hydraulic response and vice versa [1, 2], therefore the retention properties are commonly integrated in coupled soil constitutive modelling [3, 4]. Moreover, the water retention behaviour can be used to predict the variation of hydraulic conductivity of unsaturated soils [5, 6].

The water retention behaviour of soils can be defined by means of the water retention curves, which express the non-linear relationship between the suction and one of the physical parameters related to the amount of water retained inside the pores (generally the water content or the degree of saturation). As known, this relationship is suction path dependent. This peculiar behaviour results in a non-uniqueness of the water retention curve. In fact, the response to drying path (the decrease in the stored water amount usually due to drainage or evaporation) differs from the response to wetting path (the increase in the stored water amount due to imbibition or infiltration) as a consequence of the hysteric feature of the water retention behaviour. Main drying and main wetting curves represent the boundaries of the water retention domain constraining the region of the possible hydraulic conditions. Then, different values of the water content, as defined by the water retention domain, can be attainable for a given suction, as a function of the applied suction path (wetting or drying process). The hydraulic response inside the retention domain is characterized by means of the scanning lines, which define the transition between the main wetting and the main drying curves.

The water retention behaviour is deeply connected to the microstructure of the soil [7-10]. The microstructural properties can be identified in the size, shape and distribution of pores as well as in the mineralogy, morphology, spatial arrangement and bonding of the soil particles [11]. However, the water retention domain could also evolve with the variations of the void ratio of the geomaterial. This feature is significant for clays, especially when they present a double structure porosity network and, more in general, for soils which suffer significative shrinkage or swelling deformations during drying or wetting processes [12-14].

Scaly clays are strongly over-consolidated and highly fissured clays, widespread in Sicily (Italy) [15-17]. A thick network of discontinuities subdivides the clays in tightly small stiff clayey fragments (scales), almost always angular, whose size ranges from few millimetres to one centimetre. Scales are characterized by extensive arrays of elemental particle arrangements composed of particles in a very dense state and, generally, with a preferred parallel configuration. Due to their structural characteristics scaly clays can be compacted at natural water content to obtain a construction material suitable for many Civil and Environmental Engineering applications (i.e. dam cores and waste dump liners). Within this context, it is certainly of interest to analyse

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the influence of the presence of the survived scales (fragments of the strong over-consolidated clay) on the retention behaviour of the compacted geomaterial.

With this aim, the paper presents the results of a research devoted to discuss the response of this geomaterial to suction variations, in the light of the microstructural arrangement resulting from different preparation techniques. Then, the retention properties of the compacted scaly clay are compared with the corresponding characteristics of the reconstituted clay, both in normal and over-consolidated conditions. The obtained results can be considered of interest for the understanding of influence of the microstructure on the water retention behaviour since the retention domains for the same clay, in the two different microstructural arrangements, were identified in a wide suction range.

## 2 Materials and methods

The tested soil outcrops near Palermo (Sicily, Italy) and was used in the past for the construction of earth dam cores [18]. Table 1 lists the main geotechnical properties of the air-dried material such as plastic limit $w_p$, liquid limit $w_l$, hygroscopic water content $w_h$ (at relative humidity of approximately 50%), specific gravity of soil $G_s$, clayey fraction $f_{clay}$, silty fraction $f_{silt}$, sandy fraction $f_{sand}$ and activity $A = (w_l - w_p)/f_c$. From the mineralogical point of view, XRD analysis highlighted the presence of clayey minerals of kaolin, illite and mixed layers (montmorillonite).

**Table 1.** Main geotechnical properties of the air-dried material.

| $w_p$ (%) | $w_l$ (%) | $w_h$ (%) | $G_s$ ( - ) | $f_{clay}$ (%) | $f_{silt}$ (%) | $f_{sand}$ (%) | $A$ (%) |
|---|---|---|---|---|---|---|---|
| 23 | 62 | 5 | 2.76 | 56 | 40 | 4 | 0.70 |

Specimens were obtained by ad-hoc experimental techniques and several experimental methods were combined in order to explore the retention properties of the clays in a wide range of suction. In order to prepare the compacted scaly clay samples, the air-dried clay was disaggregated by a rubber pestle and the fraction passing at n° 10 ASTM sieve (mesh aperture of 2 mm) was selected. The air dried clay was added with distilled water and carefully mixed. After a curing time of 2 or 3 days, samples were compacted statically. Firstly, with the aim to explore in detail the hydraulic response, a scaly sample was compacted in a rigid metallic ring (height $h$ = 20 mm and diameter $D$ = 50 mm) and let to equalize in a suction-controlled oedometer applying a vertical net stress equal $\sigma_{vnet,0}$ = 0.2 MPa and a matric suction equal to $s$ = 0.01 MPa. The initial physical characteristics of the sample CS were the following: water content $w_0$ = 0.20, void ratio $e_0$ = 0.60, degree of saturation $S_{r,0}$ = 0.94. Axis translation technique (air overpressure method) was applied in the oedometer apparatus to control matric suction of the sample. Starting from the saturated equalized condition ($S_r$ = 1 was expected), the suction cycled between 0.01 and 0.8 MPa at constant vertical net stress $\sigma_{vnet,0}$ = 0.2 MPa. Volume and water content variations were measured during the test by means of a micrometer (resolution 0.001 mm) and a graduated burette (resolution 0.02 cm$^3$) in order to assess the void ratio and the degree of saturation variations.

With the aim to extend the information on the water retention behaviour at suction values between 2 MPa and 110 MPa, Vapour Equilibrium Technique (VET) was also adopted. Some data from a previous extensive experimental campaign on compacted scaly were also considered [19]. Scaly samples were compacted into a small rigid cylinder mould, having $h$ = 12 mm and $d$ = 15 mm; the initial physical characteristics of the considered samples were the following: $w_0$ = 0.135÷0.245, void ratio $e_0$ = 0.49÷0.95 and $S_{r,0}$ = 0.63÷0.88. The samples were set into an airtight glass jars, half filled up with aqueous sodium chloride solutions, closed in a polystyrene box placed in a controlled temperature room at 20°C. The solution controlled the relative humidity in the soil pore gaseous phase [20]. Psychometric law enabled to convert relative humidity $RH$ values in the corresponding imposed total suction $\psi$ values [21]. Water vapour transmission by simple diffusion was allowed and samples were equalized to total suction $\psi$. The imposed total suction varied between 2 and 38 MPa. Higher values of total suction were achieved by air drying samples at a temperature of 20°C and a relative humidity of 0.41÷0.48 ($\psi$ = 100÷120 MPa). Equalization conditions were obtained periodically measuring the weights (with a resolution of 0.0001 grams) and the volumes (height and diameter with a resolution of 0.001 mm) of the specimens.

The results obtained adopting VET procedures were here completed with total suction measurements by means of a dew-point water potentiometer (WP4-T, Decagon Devices). Measurements were conducted during drying and wetting paths applied on compacted samples (having initially $d$ = 35 mm and $h$ = 5.3 mm) with the same initial properties above-mentioned. The samples conditions, in terms of void ratio and degree of saturation, were also obtained immediately after the suction measurements, according to the previous experimental procedures.

Reconstituted clay samples were obtained by 1D compression of the clay thoroughly remoulded at water content greater than liquid limit ($w \approx 1.2\ w_l$). Saturated specimens were recovered from the reconstituted clay samples loaded in a consolidometer ($d$ = 96 mm; $h$ = 130 mm) to the vertical effective stress $\sigma'_v$ = 0.2 MPa. Specimens of this first series of tests on reconstituted clay, named R1, had the following initial properties: $w_0$ = 0.29 ÷ 0.35, void ratio $e_0$ = 0.81 ÷ 0.90 and $S_{r,0}$ = 1. In a second set of tests, the reconstituted saturated clay was loaded to $\sigma'_v$ = 3.6 MPa and then unloaded to $\sigma'_v$ = 0.2 MPa, in order to obtain over-consolidated samples to investigate. Specimens of this second series of tests on reconstituted clay, named R2, had the following initial properties: $w_0$ = 0.20 ÷ 0.21, void ratio $e_0$ = 0.54 ÷ 0.57 and $S_{r,0}$ = 1. These latter initial physical properties where quite similar to the ones obtained from statically compacted scaly clay tested in the suction-controlled oedometer apparatus (CS specimen).

Specimen for suction-controlled oedometric tests and for VET experiments were cored from the above-mentioned reconstituted samples and tested according to experimental procedure discussed before. In order to reduce the disturb of coring, cubic samples ($L$ = 13 mm) for VET experiments were trimmed from the reconsolidated mass. Also in this case the results were here integrated with total suction measurements by means of the dew-point water potentiometer WP4-T. Measurements were conducted during drying and wetting paths starting from saturated and air dried samples. Tested samples belonged to series R1, R2. Moreover, one other series was here considered to extend the retention properties characterization to very high initial void ratios: samples from series R3, having $w_0$ = 0.36 and void ratio $e_0$ = 0.98, were obtained applying in the consolidometer a maximum vertical stress equal to $\sigma'_v$ = 0.1 MPa while samples from series R4, having $w_0$ = 0.86 and void ratio $e_0$ = 2.37, were obtained disposing the slurry mass in the WP4-T cell.

On the base of the capability and accuracy of the WP4-T device, only suction measurements higher than 2 MPa were considered. Then, this adopted experimental procedure reduced the time of tests but, at the same time, ensured a good quality of the experimental data.

## 3 Analysis of experimental results

The hydraulic response of tested samples to drying and wetting path in the range of matric suction between 0.01 and 1.0 MPa at constant vertical net stress $\sigma_{vnet,0}$ = 200 kPa are represented in Fig. 1 and Fig. 2. In particular, results are reported, in terms of degree of saturation vs matric suction and void ratio vs matric suction, for the tests conducted on compacted scaly clay (specimen CS), on normally consolidated (NC) reconstituted clay (specimen PR2 and PR6 loaded to $\sigma'_v$ = 0.2 MPa) and over-consolidated (OC) reconstituted clay (specimen PR9 loaded to $\sigma'_v$ = 3.6 MPa and unloaded to $\sigma'_v$ = 0.2 MPa).

Starting from the saturated condition ($S_r$ = 1 and $e$ = 0.58 were obtained after equalization at $s$ = 0.01 MPa and $\sigma_{vnet,0}$ = 0.2 MPa), the compacted scaly clay started to desaturate for matric suction higher than 0.1 MPa (Fig. 1). This value can be assumed as the Air Entry Value (AEV) of the compacted scaly clay for this drying process. For matric suction higher than 0.4 MPa the drying curve assumed an almost linear trend. As effect of the drying path carried out up to 0.8 MPa, the degree of saturation decreased to 0.94 and the void ratio reduced to 0.54. In the following wetting path, the specimen did not reach the complete re-saturation; for $s$ = 0.01 MPa the degree of saturation $S_r$ = 0.989 was achieved. Moreover, in the drying/wetting cycle, the compacted scaly clay experienced a limited shrinkage strain. In fact, at the end of the wetting path the void ratio was equal to about 0.56 ($\Delta e$ = - 0.02 and $\Delta\varepsilon_v$ = 0.013).

The reconstituted clay, in this range of suction (Fig. 2), is characterized by different hydraulic and volumetric response to suction variations if compared to that of the compacted scaly clay (Fig 1). NC specimens dried significantly during the suction increasing path: at 1 MPa of matric suction, the degree of saturation was about 0.87 (Fig. 2a).

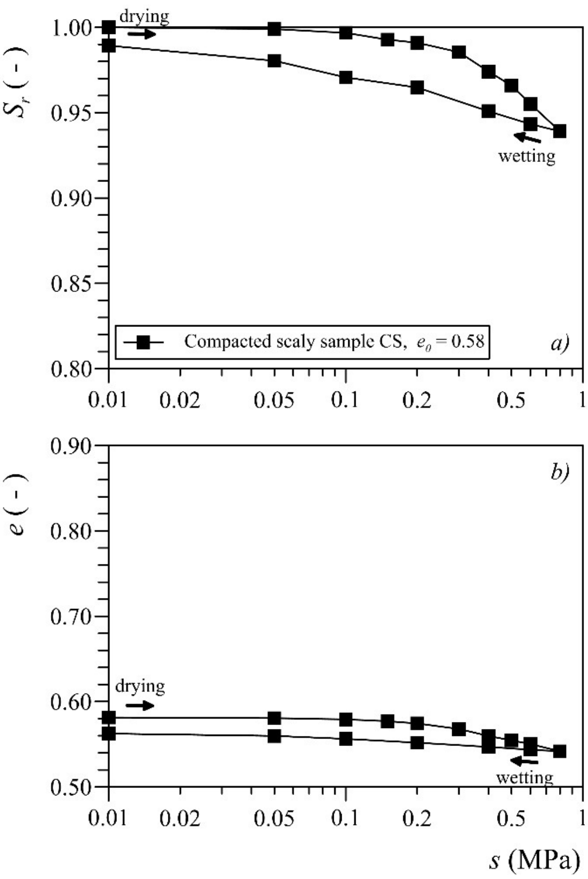


**Fig. 1.** Results of test in suction-controlled apparatus ($s$ = 0.01 ÷ 1.0 MPa) carried out on compacted scaly clay sample.

Moreover, the NC specimens significantly shrank during the tests. In fact, during the wetting path they partially recovered the positive volumetric strain, which suffered during the drying path (Fig. 2b). At the end of the drying/wetting path, the void ratio was significantly lower than the initial one ($\Delta e$ = -0.13÷-0.17 and $\Delta\varepsilon_v$ = 0.07÷0.09). The degree of saturation at the end of the suction cycles remained lower than one ($S_r$ = 0.96÷0.97). The air entry value of the NC reconstituted clay is in the range between 0.15 and 0.25 MPa: the lowest value can be considered for the specimen with highest initial void ratio (PR2, $e_0$ = 0.89) while the highest value characterized the slightly denser NC specimen (PR6, $e_0$ = 0.81). Test carried out on the OC specimen PR9 (Fig. 2) further proved that the retention properties of the reconstituted samples are clearly affected by the void ratio. Quite high air entry value (AEV = 0.5 MPa) characterizes the OC specimen. Furthermore, the specimen remained almost saturated ($S_r$ = 0.975) and limited volumetric strain was suffered ($\Delta e_{min}$ = -0.04 and $\Delta\varepsilon_{v,min}$ = 0.03) until the suction was increased to 0.8 MPa. Differently from the previous reconstituted specimen, PR9 showed an almost reversible volumetric behaviour. In fact, at the end of the drying/wetting cycle the void ratio almost returned to the initial value ($\Delta e$ = -0.005 and $\Delta \varepsilon_v$ = 0.003) and the degree of saturation was about 1 ($S_r$ = 0.99).

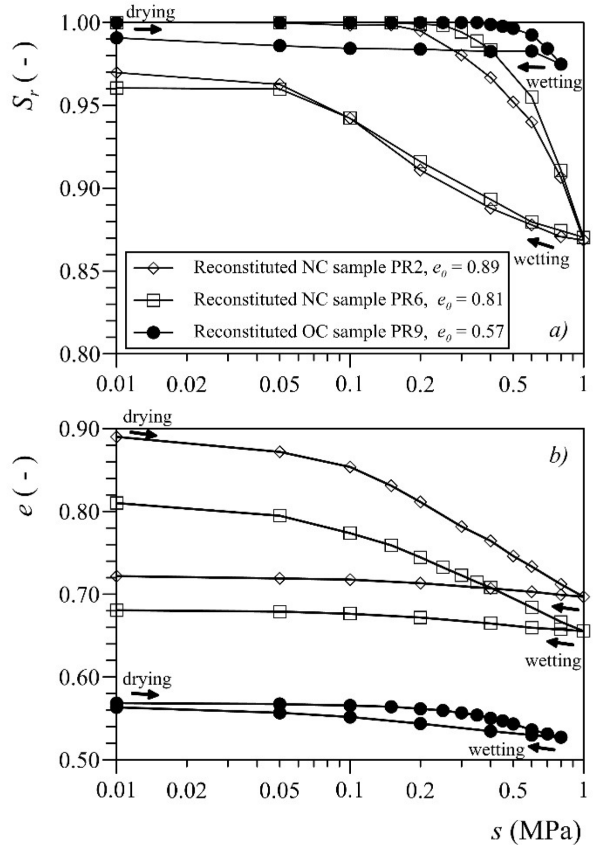


**Fig. 2.** Results of test carried out in suction-controlled apparatus ($s$ = 0.01÷1.0 MPa) on reconstituted clay samples.

The response of reconstituted samples to extreme suction variations, along drying and wetting path, is represented in Fig. 3. In particular, the results of tests carried out adopting the VET and WP4-T device are plotted in terms of void ratio $e$ and water ratio $e_w = w\,G_S$; the total suction, imposed with VET or measured by WP4-T device, of specimens is also labelled in the figure. For clarity of the diagram, only the experimental results collected on three specimens belonging to series R1, R3 and R4 are plotted. The results clearly show that the volumetric shrinkage, induced by the increasing suction, highly raises with the initial void ratio. As reported in Fig. 3, the shrinkage curves were always interpreted by means a decreasing linear trend followed by a constant volume response. The stationary behaviour characterized the specimen response when the water ratio is lower than the value $e_{w,s}$, which corresponds to the shrinkage limit $w_s$ ($e_{w,s} = w_s\,G_s$). Then, the parameter $e_{w,s}$ is deeply affected by the initial void ratio of tested reconstituted samples since it ranged between 0.33 and 0.44, which correspond to the shrinkage limit $w_s$ = 0.12 ÷ 0.16. The wetting branches, for the considered values of total suction, is characterized by a linear trend. This pattern highlighted the irreversible and hysteretic pattern of the response of reconstituted clay to suction variations.

Similar suction paths were applied on a series of scaly clay samples compacted with initial void ratio equal to 0.60 and tested according to WP4-T device procedure. These experiments were also integrated with data on compacted samples with initial void ratio equal to 0.77 and 0.95 [19] and plotted in Fig. 4. In the case of the compacted scaly clay, the shrinkage and swelling behaviour are characterized by bilinear trends and an almost constant value of shrinkage water ratio ($e_{w,s}$ = 0.3 and $w_s$ = 0.11), irrespective of the void ratio variations, could be identified.

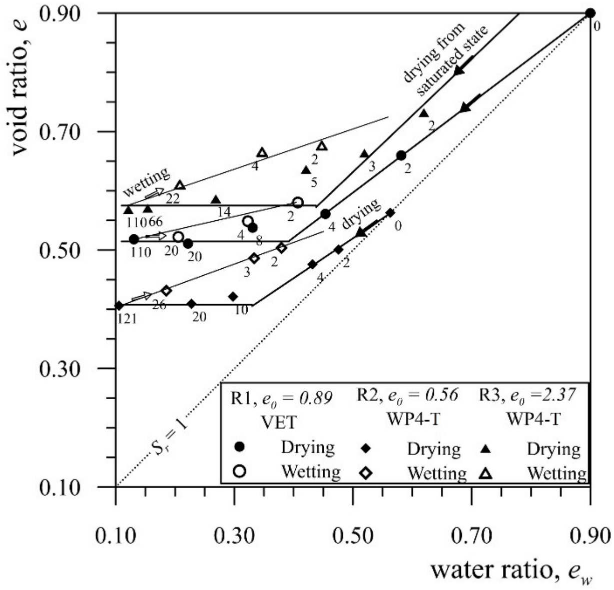


**Fig. 3.** Selection of results of test carried out with VET and WP4-T device on reconstituted clay samples with initial void ratio equal to 2.37 (series R3), 0.89 (series R1) and 0.56 (series R2). The total suction corresponding to specimens' condition is labelled close to the experimental points.

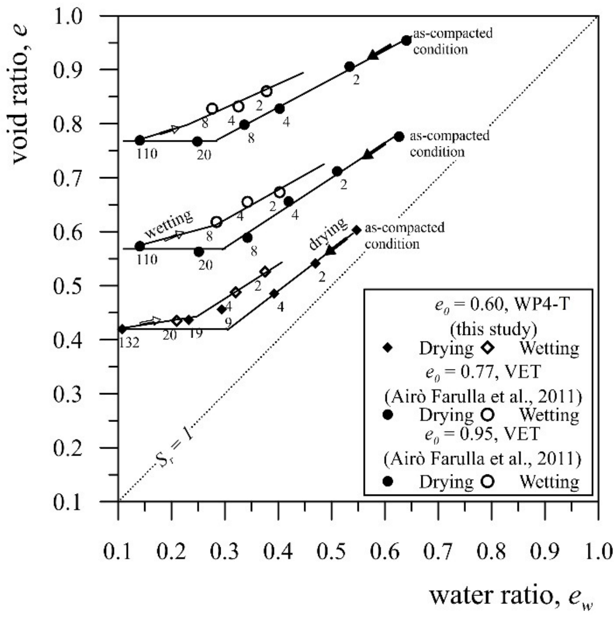


**Fig. 4.** Selection of results of test carried out with VET and WP4-T device on compacted scaly with initial void ratio equal to 0.60, 0.77 and 0.95. The total suction corresponding to specimens' condition is labelled close to the experimental points.

The overall sets of test results collected during the experimental campaigns allow to define the water retention curves for the same clayey material in the two different microstructural arrangement (compacted and reconstituted). Main retention curves were derived on the base of experimental data collected with vapour equilibrium technique, WP4-T device – for total suction values in the range 2÷110 MPa – and axis translation technique applied in the oedometric cell – for matric suction in the range 0.01÷ 1 MPa. Despite the high range of variation in the initial void ratio of reconstituted clay, a limited number of points had void ratio higher than 0.6. Then, the experimental points having a void ratio equal to 0.55 ± 0.025 were selected and plotted in Fig. 5.

Retention curves were obtained by least squares fitting of the experimental data using a modified form of the van Genuchten's equation [12]:

$$\frac{e_w - e_{w,h}}{e - e_{w,h}} = C(s)\left[\frac{1}{1+(\alpha s)^n}\right]^m \quad (1)$$

where

$$C(s) = 1 - \frac{\ln\left(1+\frac{s}{a}\right)}{\ln(2)}. \quad (2)$$

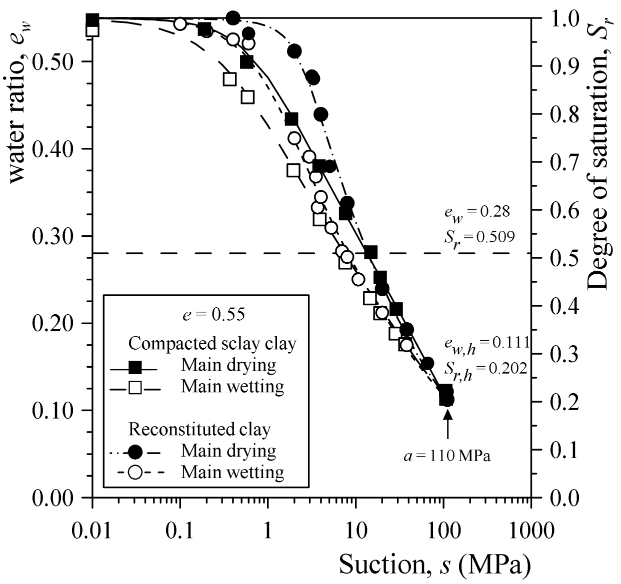


**Fig. 5.** Water retention curves at constant void ratio $e$ = 0.55 for compacted scaly clay and reconstituted clay.

The parameters *1/α*, *n* and *m* are related respectively to the air entry value or water entry value, the slope of the curve at inflection point and the residual water ratio. The residual water ratio was always set equal to the hygroscopic water ratio $e_{w,h}$ = 0.111, corresponding to the residual suction value $a$ = 110 MPa (Fig. 5). The fitted parameters are listed in Tab. 2. Data reported in Fig. 5 show that the water retention domain can be divided in two different regions: in the range of water ratio higher than $e_w$ = 0.28, the main drying and the main wetting curves of the reconstituted clay are higher than the ones of the compacted clay; instead, in the range of water ratio lower than $e_w$ = 0.28 the differences between the main curves are reduced. In this high range of suction, the main drying and the wetting curves are very close but distinct. For suction equal to 110 MPa the water ratios were substantially the same ($e_{w,h}$ = 0.111). The main drying curve of the reconstituted clay drops rapidly to $e_w$ = 0.28 when the suction exceeds the air entry value. Moreover, in the low-medium suction range the water retention domain, i.e. the area between the main drying and main wetting curves, of reconstituted clay is wider than the one of the compacted scaly with the same void ratio.

**Table 2.** Fitted parameters of the main retention curves for compacted scaly clay and reconstituted scaly clay with for $e$ = 0.55 ± 0.025.

| Scaly clay | Main curve | *1/α* (MPa) | *n* ( - ) | *m* ( - ) |
|---|---|---|---|---|
| Compacted | Drying | 0.909 | 1.400 | 0.204 |
| | Wetting | 0.606 | 1.037 | 0.321 |
| Reconstituted | Drying | 2.433 | 3.087 | 0.145 |
| | Wetting | 1.039 | 1.450 | 0.281 |

## 4 Discussion

The water retention properties of the considered clayey geomaterial can be certainly related to the microstructural peculiarities [22, 23].

Rosone et al. [24] showed that at microscopic level, compacted scaly clays present an aggregated structure with a clear double porosity network, in which two principal levels of pores can be identified: micro pores inside aggregates and macro pores between aggregates and assemblages. Aggregates are made mainly of scale fragments (which are not eliminate by compaction), even if other different particle assemblages, typical of clay compacted on the dry side of the optimum moisture content, can be observed.

Airò Farulla et al. [25] showed that the reconstituted scaly clay is characterized by an open microstructure with a pronounced pore mode. The modal pore value is greater than the corresponding values of the intact scales but lower than the modal value of macropore in compacted scaly clay. However, the pore size distribution in reconstituted clays is strongly affected by loading. However, Airò Farulla et al. [24] highlighted that it is possible to individuate small aggregates which survived to intense remoulding procedures.

The observed behaviour can be interpreted by considering the different water retention mechanisms which characterize the widest pores (macropore in compacted clay and modal pores in reconstituted clay) and the and the smallest pores (pore inside aggregates and pores between individual particles). In the low-medium suction range, i.e. when $e_w$ > 0.28, water is enough to partially fills the widest pores as bulk water and to form menisci in the air filled voids. Then, the mechanism of water storage which prevails in this region is the capillarity. The latter is dependent on void ratio and mechanical actions which modify the macropore volume. As suction increases, volumetric strain increases in the saturated zone, as a consequence of the effective stress increase, while in the curvature of menisci in the air filled voids increase. As suction further increases, some saturated pores empty and the effect descripted before becomes less and less noticeable. This justifies the high volumetric shrinkage, experienced in the first part of shrinkage curves, and the constant-volume shrinkage behaviour observed both in Figs. 1 and 2.

In the high suction range, i.e. the $e_w < 0.28$, water is present only in the smallest pores (inter-particles pores) while the largest are completely dry. In this region, water adsorption by clay particles becomes the dominant mechanism of retention. Adsorption mechanism only depend on mineralogical clay properties, as specific surface and plasticity. For this reason, it can be expected that the retention properties of the same clay with two different particles arrangement can be substantially the same in the high suction range.

## 5 Conclusions

Collected results highlighted the significant role of the microstructural features on the retention behaviour of a compacted and reconstituted scaly. The first was obtained by static compaction after moistening of an air-dried scaly clay while the second was obtained by 1D compression of the clay thoroughly reconstituted at water content greater than the liquid limit. Several experimental techniques (vapour equilibrium technique, dew-point water potentiometer suction measurements and axis translation technique) were combined in order to explore the retention properties of the clays in a wide range of suction.

Due to the quite high shrinkage strain experienced by the reconstituted clay during the drying path from the saturated state, it was better to provide a comparison of behaviour of the two geomaterial considering a constant void ratio ($e$ = 0.55). Collected data showed that the water retention domain can be divided in two different regions considering a water ratio $e_w = 0.28$. The analysis of the retention behaviour of the first region (low-medium suction range, $e_w > 0.28$) showed that the microstructure which was realized with clay compaction is detrimental with regard of the retention properties. In fact, the main drying and the main wetting curves of the reconstituted clay are higher than the ones of the compacted clay. Instead, in the second region (high suction range, $e_w < 0.28$) the differences between the main retention curves are reduced. These peculiarities depend on the retention mechanisms which prevails in the two regions: capillarity, in the first region, bring the two materials to react differently to suction variation while adsorption mechanism, in the second region, brings the two materials back to realign in the water retention behaviour.

In conclusion, the collected results permitted to define the retention domains on the base of different microstructural arrangement and a constant mineralogy. These results could also contribute to elaborate a model where the evolution of the microstructure with weathering agents (like atmosphere, rainwater, rising groundwater table and so on) could be taken into account.

## References

1. V. Escario, J. Saez, Géotechnique **36**, 3, 453-456 (1986)
2. E. Alonso, A. Gens, A. Josa, Géotechnique **40**, 3, 405-430 (1990)
3. L. Laloui, M. Nuth, Comput. Geotech. **36**, 1–2, 20–23 (2009)
4. D. Sheng, S.W. Sloan, A. Gens, A. Comput. Mech. **33**, 6, 453-465 (2004)
5. Y. Mualem, Water Res. Research., **12**, 513-522 (1976)
6. D.G. Fredlund, A.Q. Xing, S.Y. Huang, Can. Geotech. J., **31**, 521-532 (1994)
7. J.A. Muňoz-Castelblanco, J.M. Pereira, P. Delage, Y.J Cui, Géotechnique, **62**, 2, 95-106 (2012)
8. E. Romero, Eng. Geol., **165**, 3-19 (2013)
9. M. Rosone, C. Celauro, A. Ferrari, Int. J. Pavement Eng. (in press) (2018)
10. M.P. Cordão Neto, O. Hernández, R. L. Reinaldo, C. Borges, B. Caicedo, Earth Sci. Res. J., **22**, 2, 91-101 (2018)
11. J.K. Mitchell, K. Soga K., *Foundamentals of Soil Behavior* (John Wiley and Sons, Hoboken, NJ, 2005).
12. E. Romero, J. Vaunat, *Experimental Evidence and Theoretical Approaches in Unsaturated Soils*, 91-106 (2000)
13. S. Salager, M. Nuth, A. Ferrari, L. Laloui, Can. Geotech. J., **50**, 2, 200-208 (2013)
14. M. Rosone, C. Airò Farulla, A. Ferrari, C. Torta, C. Celauro, E3S Web Conf., **9**, 14020 (2016)
15. C. Airò Farulla, F. Cafiso, F. Calvi, M. Rosone, Riv. It. Geotec., **49**, 1, 7-28 (2015)
16. M. Rosone, M. Ziccarelli, A. Ferrari, C. Airò Farulla Eng. Geol., **235**, 20-38 (2018)
17. M. Rosone, M. Ziccarelli, A. Ferrari, *Lecture Notes in Civil Engineering*, **40**, 195-204 (2020)
18. C. Airò Farulla, C. Valore, *International Symposium on Hard Soils and Soft Rocks*, **1**, 335-342 (1993)
19. C.A. Farulla, A. Battiato, A Ferrari. *5$^{th}$ International Conference on Unsaturated Soils,* 417-422 (2011)
20. E. Romero, *4º Simpósio Brasileiro de Solos Não Saturados*, 535-542 (2001)
21. D.G. Fredlund, H. Rahardjo, *Soil mechanics for unsaturated soils* (John Wiley and Sons, 1993)
22. R. Monroy, L. Zdravkovic, A. Ridley, Géotechnique, **60**, 2, 105-119 (2010)
23. W.-J. Sun, Y.-J. Cui, Géotechnique, **68**, 4, 370-373 (2018)

24. M. Rosone, C. Airò Farulla, A. Ferrari, Acta Geotech. **11**, 37-50 (2016)
25. C. Airò Farulla, M. Rosone, *XV European conference on soil mechanics and geotechnical engineering, ISSMGE*, 107-113 (2011)