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Influence of structure in the soil-water characteristic curves of two residual soils of granite

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Abstract. This paper discusses the influence of structure in the soil-water characteristic curves (SWCC) of two residual soils of granite formed in a subtropical environment. One soil has a saprolitic nature (named GrSp) and the other shows lateritic behavior (named GrLt). Both materials occur on a slope which presents a extensive history of landslides in the municipality of São José, Southern Brazil. SWCC of undisturbed and remolded specimens were determined using the filter-paper technique. Undisturbed specimens were collected and remolded specimens were produced by static compression of disintegrated soil to the same void ratio and moisture content of undisturbed specimens. SWCC of saprolitic soil showed curves which were modelled as unimodal but the lateritic soil required the use of bimodal curves because of the structure developed in micro and macro levels. Suction levels measured in GrLt soil were higher than in saprolitic soil. Remolding process changed the levels of suction achieved, which is due to the structure and more specifically to the size of pores in the remolded soils. Hysteresis were verified in both materials, but were far more pronounced in the lateritic soil. Analysis of mercury intrusion porosimetry were carried out in GrSp soil. They showed that remolding generates a different pore distribution from the existing in the undisturbed soil.

1 Introduction

Geomechanical properties of residual soils may be affected by the action of macro and microstructure features developed by weathering processes [1]. Soil structure refers to combined effect of particle, groups of particles and pores arrangement, composition and forces between particles [2]. Similar definition for soil structure was proposed by [3, 4].

While structure origins may be complex, the effects themselves may be described in a simple and general way [5].

The term structure is used by [5,6] to refer to those soil features which are peculiar to the soil in its undisturbed condition, as inter-particles bonding or cementation, and are eliminated when the soil is remolded.

Thus, investigation of macrostructure effects on soil behavior may be carried out through evaluation of possible differences exhibited in tests carried out using undisturbed and disturbed specimens. Undisturbed (or natural) specimens must be obtained through high quality sampling. Disturbed specimens should be obtained by remolding, compaction or reconstitution, in order to remove structural elements of soil.

In [7, 8] is mentioned that water retention depend of many features, such as amount, size and distribution of pores, soil texture and mineralogy. Thus, the structure developed with the formation of residual soils should influence on suction levels that should be mobilized in such materials, when they are unsaturated.

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Although there are many papers reporting the determination of soil-water retention curves (SWCC) for residual soils, most of them carried out test in compacted specimens [8-13] or undisturbed specimens only [14-19, 7].

There are few studies discussing the effects of structure loss on SWCC. In this sense [20] should be mentioned. The authors present SWCC of volcanic soils from Honk Kong both in undisturbed and recompacted specimens.

This paper presents the results of SWCC for two tropical residual soils of granite from Southern Brazil, obtained though filter-paper tests in undisturbed and remolded specimens. One of these soils is a saprolite and the other exhibits some lateritic features.

2 Characterization of studied soils

Both soils are residual of the same granite rock and occur in São José (SC) municipality (Figure 1). These soils are found in a slope 120 m height, which has suffered successive instabilities. The coordinates of the sampling area are 732.370 E and 6.948.100 S with an average altitude of about 53 m above sea level.

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The elevations of this region are formed by Neoproterozoic granites that forms Dom Feliciano Belt [21,22], which extend from Santa Catarina state, Brazil, to Uruguay.

Figure 1. Localization of São José Municipality

The saprolitic residual soil is named GrSp. This soil occurs in the whole area of the slope but mostly as a layer subjacent to the soil here named GrLt. The GrLt soil shows some features which are typical of lateritic soils, but it is not a laterite. The manner in which these soils occur is illustrated in Figure 2 while Figure 3 shows each soil in detail.

Figure 2. A profile view of both studied soils.

Figure 3. Close view of GrSp soil (left) and GrLt (right).

Physical index and classification of these soils are presented in Table 1 and grain size distributions are shown in Figure 4.

Table 1. Physical properties and classification indexes of studied soils.

	GrSp	GrLt
G	2,625	2,699
w_{nat} (%)	29,0	30,0
γ_{nat} (kN/m³)	16,84	15,65
γ_d (kN/m³)	13,04	12,05
γ_{sat} (kN/m³)	17,88	17,39
e	0,97	1,20
Sr (%)	78,5	67,0
wL	42	60
PI	18	24
USCS	ML	MH

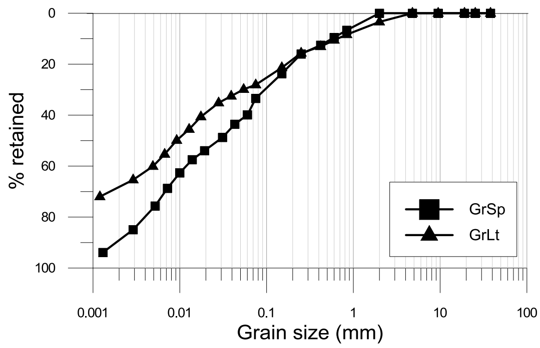

Figure 4. Grain size distribution of studied soils.

The GrLt soil presents a larger amount of fine particle than GrSp although the clay particles naturally occur as concretions or clusters resulting in a rough texture similar to a sandy soil. However, the clayey nature of the soil is reflected in its grain size distribution curve and in its high PI.

From the mineralogical point of view these materials show different compositions (Table 2), despite the same origin rock. This highlights the different weathering level.

Table 2. Mineralogical composition of studied soils (semi quantitative data from X-ray diffraction analysis)

	GrSp	GrLt
Quartz	13 %	30 %
Plagioclase	68 %	24 %
Biotite	-	19 %
Kaolinite	13 %	27 %
Chlorite	8 %	

3 Experimental program

3.1. Soil-water characteristic curves (SWCC)

Determination of soil-water characteristic curves (SWCC) was carried out through the filter-paper technic based in recommendations made in [23] as well as suggestions of [24] based in the experience with tropical soils from Southern Brazil.

The SWCC of GrSp and GrLt were obtained using undisturbed and remolded specimens which 50 mm in diameter and 20 mm height. These remolded specimens were produced in order to achieve void ratio, density and moisture content similar to undisturbed specimens.

Whatman nº 43 filter paper were used. According to [25] it is able to reach moistures between 5% and 175% (suctions between 29,000 kPa and 3 kPa). The correlation between suction (Ψ) and paper moisture (w_f) is given by Equation 1 (when w_f <45,3) and Equation 2 (when $w_f \geq$ 45,3) as proposed in [23].

$$log\psi = 5{,}327 - 0{,}0779 \cdot w_f \tag{1}$$

$$log\psi = 2{,}413 - 0{,}0135 \cdot w_f \tag{2}$$

Although [23] mentions that the equations are only valid for measurement of the total suction [26] demonstrated that there is only one calibration curve for the filter-paper method regardless the type of suction that is being measured.

Differently of proposed in [23] the tests were carried out using one filter-paper positioned in contact on just one soil specimen side and not between two specimens. This procedure has the advantage of using a smaller quantity of soil for testing and the ease in controlling the moisture of a single specimen. This proposition was presented by [24].

An interface paper was also used between the soil and the paper used to measure suction. This interface paper was not exchanged during the test. The paper was kept in contact with soil for seven days protected from the light and temperature variations.

The first suction level measurement was made in natural moisture condition. After that it was performed a wetting cycle followed by a drying cycle and a new wetting cycle. Changes of soil moisture were made in steps of 5% in saturation degree.

3.2 Pore-size distribution

Mercury intrusion porosimetry technic (MIP) has been employed by many researchers in order to investigate soil structural features as [27-31] and others. Distribution, size and connectivity of pores may be used to define mechanical and hydraulic properties of soils [32, 33].

Two specimens of GrSp soil were submitted to MIP analysis. One of them was extracted from an undisturbed block. The second one was obtained from a specimen remolded from disaggregated soil similar to those used for the determination of the SWCC (similar physical indices as in undisturbed condition).

The specimens were air-dried and after that oven-dried at 40º C. Some authors [28-30, 15] report that in clays oven drying is not appropriated because causes shrinkage and pore diminution, mainly when samples are prepared as slurry. In this case, according to such authors, sample freezing and subsequent sublimation for water extraction is a more appropriate drying procedure.

In this research the option for air-drying is justified because when the determination of SWCC is carried out, the soil is air-dryed. Therefore, suctions under specific degree of saturation are associated to soil volumetric changes. Besides, because the specimens are not prepared as slurry, there was little significant shrinkage during drying.

The equipment used to MIP analysis was an AutoPore IV – Micromeritics following procedures described in ISO 15901/2005. Measurements of intruded volume were done through stepwise mode. The physical parameters of mercury used for the interpretation of analysis were density of 13.54, superficial tension of 0,485 N/m and contact angle of 130º

4 Results and Discussions

Figure 5 shows SWCC obtained for GrSp soil in undisturbed and remolded conditions and experimental points.

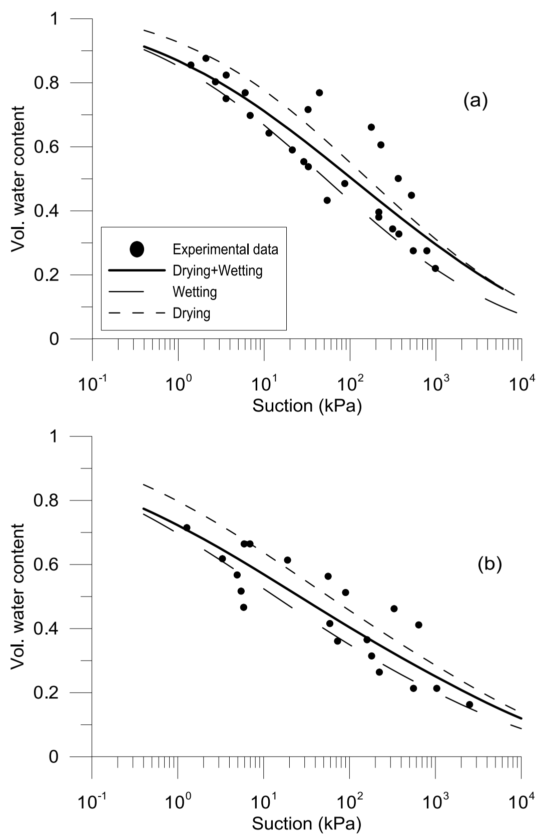

Figure 5. SWCC of GrSp soil (a – undisturbed, b – remolded).

For undisturbed and remolded specimens there are differences between the curves obtained from drying and wetting data points indicating hysteresis. Drying curves are situated above wetting curves. For the undisturbed soils, suction values less than 1 kPa occur when volumetric water content is higher than 90% (w=31% and Sr=78%). For the remolded soil such suction level stands to volumetric water content of 70%.

When the behavior of undisturbed and remolded are comparedit seems that degradation of soil structure by remolding reduces suction levels that are mobilized. Thus, under same moisture content undisturbed soil develops higher suction levels than the remolded specimen.

SWCC to express the relationship between suction and saturation for GrSp soil showed in Figure 5 follow the model proposed by [34], according Equation 3.

$$\theta = \theta_s \left[\frac{1}{ln\left[e + \left(\frac{\psi}{a}\right)^n\right]} \right]^m \cdot \left[1 - \frac{ln\left(1 + \frac{\psi}{\psi_r}\right)}{ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \qquad (3)$$

Where : θ – volumetric water content θ_s – volumetric water content for saturation; ψ – suction; ψ_r – suction under residual moisture; *a, m, n* – fitting parameters.

The parameters used to adjust the curves for GrSp soil are shown in Table 3.

Table 3. Fitting parameters for GrSp.

	Undisturbed			Remolded		
	W/D	Dry.	Wet.	W/D	Dry.	Wet.
a	72,51	74,72	71,00	13,68	13,68	13,68
n	0,351	0,416	0,375	0,295	0,321	0,287
m	0,976	0,854	1,171	0,886	0,784	1,078
θ_{sat}	1,056			1,011		

The SWCC for GrLt soil in undisturbed and remolded specimens are shown in Figure 6 including experimental data points.

In this Figure it is possible to verify a strong hysteresis while in remolded specimen this phenomenon is less marked. In undisturbed condition for volumetric water content levels higher than 75% (degree of saturation about 65%), small suctions are measured, in general below 10 kPa.

Comparing the results of SWCC for undisturbed and remolded sample is possible verifies that fitted curves refers to the development of higher suction in remolded specimen than in undisturbed one. These results are opposite to the obtained in GrSp soil.

The behavior of GrLt soil is not well reproduced by Fredlund and Xing (1994) model and it necessary the use of a bimodal model. In this sense [35-36] pointed out that unimodal curves could not be used to reproduce the behavior of many residual or sedimentary soils originated in tropical or subtropical environments.

According to [24] this occurs because these soils often exhibit well-defined micro and macro structures being composed for clay particles which are aggregated forming clay clusters of silty and sandy size and may have some behavior of those.

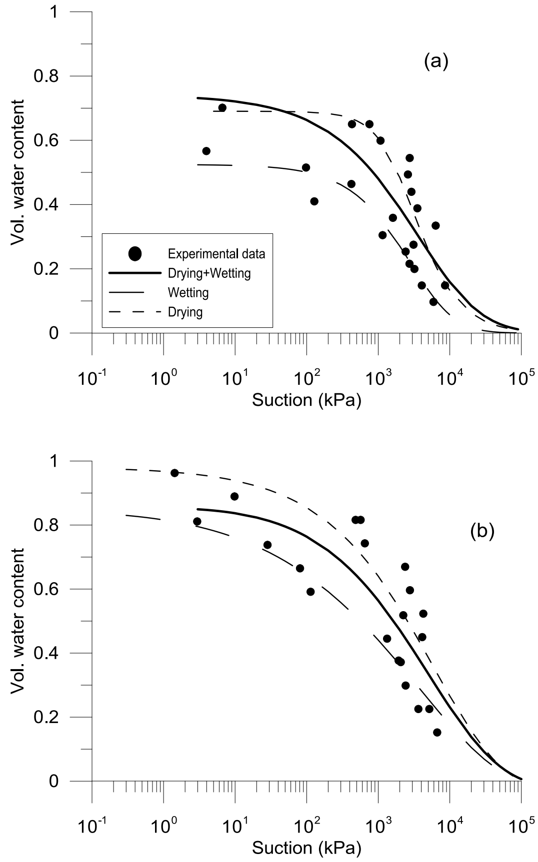

Figure 6. SWCC of GrLt soil (a – undisturbed, b – remolded).

The shapes of SWCC in these materials suggest a bimodal pores distribution: macro pores between clay clusters and micro pores inside the clusters. So, a model proposed by [37] was used to modeling the curves for GrLt soil (Equation 4)

$$\theta = \theta_s \left[\left[\frac{s_1}{ln\left[e + \left(\frac{\psi}{a_1}\right)^{n_1}\right]^{m_1}} \right] - \left[\frac{1 - s_1}{ln\left[e + \left(\frac{\psi}{a_2}\right)^{n_2}\right]^{m_2}} \right] \right] \cdot \left[1 - \frac{ln\left(1 + \frac{\psi}{\psi_r}\right)}{ln\left(1 + \frac{10^6}{\psi_r}\right)} \right] \qquad (4)$$

Where: s – saturation degree that divide the curve in low and high suction levels; θ – volumetric water content; θs – volumetric water content in saturation; ψ – suction; ψr – suction under residual moisture; a_i, m_i, n_i – fitting parameters.

The parameters used to adjust the curves for GrLt soil are shown in Table 4.

Although a bimodal model is useful it was not possible to fit a curve over a wide suction range so that it could had a "classic" bimodal curve. This is because: (i) under moisture contents larger than 27% the suction drops to levels below 1 kPa were the filter paper method is not valid; (ii) suction levels higher than 8 MPa were not achieved in the tests, requiring another techniques for that.

Comparing Figures 5 and 6, one verifies a more pronounced hysteresis in soil GrLt than in GrSp both in undisturbed and remolded condition. There is no clear evidences about the cause, but is possible correlates a less pronounced hysteresis between wetting and drying curves with a smaller amount of fines and consequently lower level of weathering.

Figure 7 shows the SWCC for both soils plotted in the same space. These curves were fitted using both drying and wetting experimental data.

Table 4. Fitting parameters for GrLt.

	Undisturbed			Remolded		
	W/D	Dry.	Wet.	W/D	Dry.	Wet.
a_1	24000	2283	10000	8000	15000	10000
n_1	0,600	1,800	0,907	0,5	0,5	0,364
m_1	3,00	0,550	3,00	1,2	1,45	1,416
a_2	45000	45000	45000	44689	44633	40000
n_2	0,08	0,08	0,08	0,104	0	0,05
m_2	25	25	25	0,927	0,747	0,744
S_1	0,5	0,46	0,35	0,770	0,793	0,762
ψ_{res}	12000	12000	12000	12000	12000	12000
θ_{sat}	1,483			1,465		

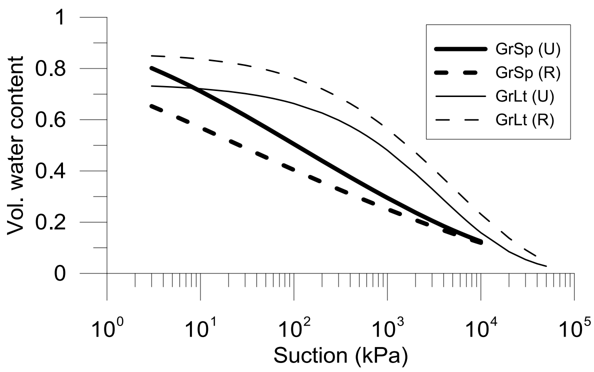

Figure 7. Fitted SWCC for GrSp and GrLt.

It is noted that the mobilized suction levels are proportional to the fines content and degree of weathering for undisturbed and remolded conditions. However, for a volumetric water content higher than 70% GrSp soil was able to maintain suctions slightly higher than GrLt, if compared results from undisturbed specimens.

Figure 8 shows the pore size distribution for the GrSp soil both in undisturbed and remolded conditions.

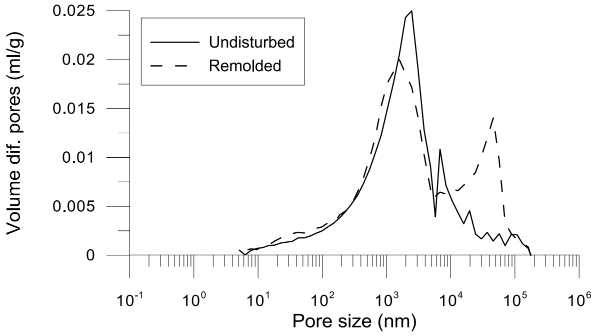

Figure 8. Pore size distribution in GrSp specimens.

Figure 8 shows a clear difference between pore size distributions in both samples. The number of pores in the range of 10^3 and 10^4 nm are reduced when the soil is remolded but a large amount of pores in 10^4 and 10^5 nm range are developed. It means that if the soil is remolded a larger number of bigger pores are produced than it is found in the undisturbed specimen. Thus, larger pores desaturate at lower suction levels and consequently SWCC of remolded sample indicate lower suctions than in undisturbed sample for the same volumetric water content.

5 Conclusions

The SWCC obtained for saprolitic soil (GrSp) is unimodal but for the lateritic (GrLt) a bimodal curve fitting was required. This seems to be due the structure developed in a macro and micro levels along the lateritization process. Suctions measured in lateritic soil are, in general, higher than in the GrSp.

The remolding process affects the suction curves obtained. This was caused by changes in soil structure specifically related to pores and clayey clusters size developed after remolding. The GrLt soil is more sensible to remolding and in this condition higher suction levels are achieved than when undisturbed. In the GrSp soil the opposite was observed.

Mercury intrusion porosimetry (MIP) analyses in GrSp soil showed that remolded specimensat the same voids ratio, density and moisture as the undisturbed, showed a distinct pore configuration. In remolded condition, soil has larger pores and therefore the suctions are lower than those measured in undisturbed specimen. This behavioral change is caused by structural changes since the relationship between pore size and suction is very strong as shown in [17, 14, 38].

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