Geotechnical characterization of two unsaturated mature granite residual soils from Pernambuco, Brazil

R.Q. Coutinho, M.M. Silva and K. Lafayete
Department of Civil Engineering – Federal University Pernambuco, Recife / Pernambuco, Brazil

ABSTRACT
This paper presents results of geotechnical characterization of two unsaturated mature granite residual soils from two research areas of Recife Metropolitan Region, Pernambuco, Brazil, where research were done due to the occurrence of landslide (city of Camaragibe) and erosion (city of Cabo) processes. The geotechnical characterization of these materials was performed including physical characterization, soil-water characteristic curve and shear strength in saturated and unsaturated condition. The soil-water characteristic curve was obtained through filter paper method, Haines Funnel and Richards pressure Chamber. The shear strength parameters were determined using direct shear tests (saturated condition) and direct shear tests with controlled suction, with suction varying from 0 - 500kPa (unsaturated condition). The results were discussed and compared with literature presenting satisfactory values.

RÉSUMÉ
Cet article présente les résultats de la caractérisation géotechnique de deux sols résiduels insaturés de granit de deux terrains de recherche situées a villes (Camaragibe et Cabo) dans l'etat de Pernambuco, Brésil. La caractérisation géotechnique de ce matériel a été exécutée comprenant la caractérisation physique, la courbe caractéristique de la sol-eau et la resistance au cisailhement a l'etat saturé et non saturé. La courbe caractéristique sol-eau a été obtenue par la méthode de papier filtre, l'entonnoir de Haines et la chambre de la pression de Richards. Les paramètres de résistance au cisaillement ont été déterminés utilisant les essais de cisaillement direct (état saturé) et cisaillement direct avec suction controlée, avec la variation de suction de 0 - 500kPa (état insaturé). Les résultats ont été discutés et comparés à la littérature présentant des valeurs satisfaisantes.

1 INTRODUCTION

Unsaturated soils in their various categories (residual soils, collapsible soils, expansive soils and so forth) can be found almost everywhere in the world. Their importance in the geotechnical field came to be recognized with the development of the arid, semi-arid and tropical regions causing engineers to work on soils showing geotechnical behavior different than those predicted according to the principle of effective stress (PES) which has been developed for saturated soils and temperate climate. Fredlund (2006) illustrates the progression from the development of theories and formulations to practical engineering protocols for a variety of unsaturated soil mechanics problems (e.g., seepage, shear strength, and volume change). The ground surface climate is a prime factor controlling the depth to the groundwater table and therefore, the thickness of the unsaturated soil zone. The zone between the ground surface and the water table is generally referred to as the unsaturated zone. The water degree of saturation of the soil can range from zero to 100%. In residual soils or in tropical soils in general, the water table is in many cases deep in the profile; hence the soils are generally in unsaturated conditions. In this case, the role of matrix suction and its effect on the soil behavior has to be recognized and considered in the interpretation of in situ and laboratory tests.

This paper presents results of geotechnical characterization of two unsaturated mature granite residual soils from two areas of Recife Metropolitan Region, Pernambuco state, in the northeast of Brazil. In these areas study were performed up part of doctorate researches that aims to give continuity to studies that are relative to understanding of mechanisms of instability of slopes and erosion process, carried out by the Geotechnical Group of the DEC/UFPE which had the support of the PRONEX-CNPq/FACEPE project.

The first research area is localized in the city of Camaragibe, which belongs to the west part of Recife Metropolitan Region. The landslide that occurred was classified as a multiple rotational landslide, characterized by the appearance of various steps along the slope. The area under study presents, as geological characteristics, an unsaturated residual soil of granite that is partially covered by the Barreiras Formation. The residual soil of granite is found in the entire city. In some places it is possible to have granite rock exposed. The results presented here are referring to the study of the characteristics of the residual soil involved in the mass movement.

In the Recife Metropolitan Region is common to found crystalline based rocks (Granite-Gneissic complex) covered by residual soil of granite, originated from the crystalline; and by the sediments from Barreiras Formation. The crystalline base is formed by intrusive rocks of archaic age (1.5 a 21 billion years) belonging to

Maciço Pernambuco – Alagoas (Alheiros 1998). It presents at least four phases of deformation, of which the latter, associated to the faults under deformation regime, resulted in the Formation of the "Pernambuco Lineamento".

The second research area is localized, in the city of Cabo, which belongs to the south part of Recife Metropolitan Region. In this area there is a strong erosion process. The area under study presents, as geological characteristics, an unsaturated granite residual soil that is partially covered by the Barreiras Formation. There are also places with granite rock exposed. The results presented are referring to the study of the characteristics of the residual soil involved in the erosion process.

2 GEOTECHNICAL CHARACTERIZATION

In the two doctorate researches an extensive campaign of in situ and laboratory investigation were carried out (Lafayete, 2006; Silva, 2007).

For the basic geotechnical characterization the Laboratory campaign consisted of physical, chemical and mineralogical characterization tests, strength tests (included direct shear tests and direct shear tests with controlled suction) and edometric tests,

The emphasis in this paper was given for obtaining the characteristic curves by methods of filter paper, Haines Funnel and Richards pressure Chamber and direct shear test in submerged condition and with controlled suction.

2.1 Physical characterization

The mature granite residual soil studied in the research area 1 (Camaragibe) presents a fine texture, with a liquid limit of 54%, plasticity limit of 32% (IP=22%), with grain size distribution of 39% of clay, 26% of silty, 23% of fine sand and 12% of medium and thick sand. The soil is classified as CL in the Unified Classification System (USCS).

Granulometric tests without the use of deflocculant also were performed, where the grain size distribution found was 5% of clay; 33% of silty; 50% of fine sand and 12% of medium and thick sand.

These results are compared in Figure 1 showing a strong reduction in the fraction of clay and increased in the fine sand fraction, indicating that the particles of clay in this soil are found to be aggregated in their natural state.

The mature granite residual soil studied in the research area 2 (Cabo) presents also a fine texture, with a liquid limit of 62%, plasticity limit of 28.6% (IP=28.6%), with grain size distribution of 71% of clay, 05% of silty, 21.5% of fine sand and 2.5% of medium and thick sand. The soil is classified as CL in the Unified Classification System (USCS). The granulometric test without the use of deflocculant presented a grain size distribution of 5% of clay; 33% of silty; 50% of fine sand and 12% of medium and thick sand, indicating that the particles of clay in this soil are strongly aggregated in their natural state.

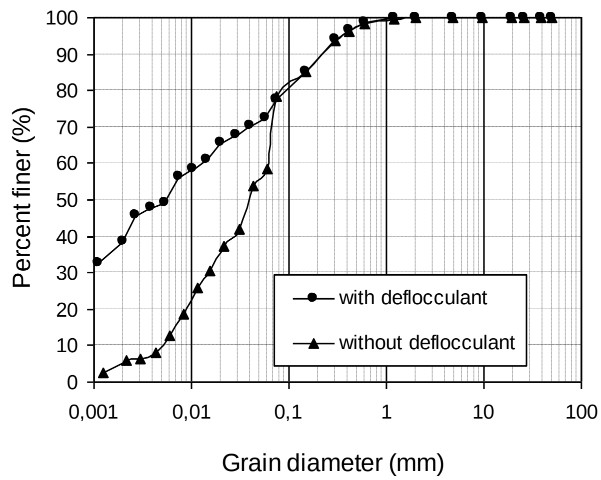


Figure 1. Granulometric test results – area 1.

2.2 Soil-water characteristic curve

To study the behaviour of unsaturated soils, it is essential to know the relationship between the amount of water in a soil and the soil suction – the soil-water characteristic curve. SWCC can be determined from both laboratory (more common) and in-situ tests by controlling or measuring both the water content and soil suction.

SWCC of a given soil can be influenced by many factors, e.g. initial specimen properties (including initial water content, initial dry density and compaction method), soil structure (recompacted or natural), drying and wetting cycle, stress history and current stress state (Ng & Chen, 2008). Ng & Chen (2008) present an interesting discussion and results about the influence of some of these factors on SWCC, including drying and wetting circles, the stress level, recompacted or natural specimens and laboratory and in-situ SWCC.

2.2.1 Methodology employed

In this work, the soil water characteristic curves presented were obtained by the filter paper method, Haines Funnel and Richards pressure Chamber, in the usual procedure with net vertical stress of 0 kPa.

The determination of the characteristic curve through the paper filter method is based on the principle that a soil, when placed in contact with a paper filter in a hermetically sealed ambient, makes the latter absorb a certain quantity of water from the soil until the system enters into equilibrium of pressure. In this condition, the paper and the soil will have the same suction, although having different gravimetric water content. Knowing the retention curve of the paper (suction – water content relation) and its gravimetric water content, the suction of the paper is determined. In the present research, the drying and the wetting curve were obtained. The paper filter used was Whatman number 42 type 2, which allowed suction measurements of zero up to 29 MPa (Marinho 1995). For determination of the matric suction, the undisturbed samples were molded in metallic rings of 7,20cm in diameter and 3,0 cm in height. Each group (paper filter + sample) was protected by a plastic film of PVC and by a paper aluminum foil. The equilibrium time used was approximately seven days. The wetting process of the samples was carried out with the aid of a water nebulizer and waiting a minimum of two hours for placing the paper filter guaranteeing a better homogenization between the sample and water. During the drying the samples were exposed to room temperature.

For determination of the soil-water characteristic curve was also used equipment known as Richard´s pressure chamber. Figure 2 presents details of the pressure chamber equipment. This equipment can be used as much in deformed samples as in undisturbed samples, allowing the extraction of humidity from the soils by the drying process up to 1500 kPa. The Richard´s pressure chamber is made up of a chamber for supporting high pressures, with its inside face being covered by a rubber diaphragm, that is sealed at its border. Two undisturbed samples were moulded in PVC rings of 5cm in diameter and 1cm in height, and taken to the Richard´s pressure chamber, where the suctions applied were 34kPa and 1549kPa. At the point of equilibrium (normally after 10 days from the beginning of the test) the applied suction was switched off, and each ring was weighed. Then the samples were taken to the heater for determination of their humidity.

The Haines funnel is equipment that is used for determination of soil suction, only for low tension points of the characteristic curve. The samples were moulded in PVC rings of 5.2 cm in diameter and 2.5 cm in height. Then water was added up to saturation around 24 hours. After this phase the excess water was removed and pipette was adjusted, levelling the meniscus to the tension level of 0 cm marked on the support. Suctions of 0,1 kPa; 0,3 kPa; 0,5 kPa;1,0 kPa; 1,5 kPa; 2,0 kPa; 3,0 kPa; 5,0 kPa; 7,5 kPa and 10 kPa were applied. The superior part of the funnel was covered with plastic, so as to avoid loss of humidity by evaporation. Figure 3 illustrates the equipment.

The use of these equipments had the objective to obtain an adequate complete curve. Good results using these three techniques were also found by Silva & Coutinho (2007) for an unsaturated soil of the Barreiras Formation.

2.2.2 Results

The soil-water characteristic curve obtained through the paper filter, Haines funnel and Richard´s chamber method is presented in Figure 4. The format of the curve shows a “saddle” aspect, being able to be divided into three distinct stretches. The curves indicate an initial air entry suction of 1kPa, where there is the start of desaturation. After that an approximately horizontal region is observed, where the suction varies from 20 to 200kPa. In the last stretch occurs a second air entry value, where the water content starts to diminish with the increase in suction due to the removal of water from the soil micropores.

For the granite residual soil studied, during the wetting and drying processes, the results are very close, making it difficult to identify any effect of the hysteresis (Figure 4).

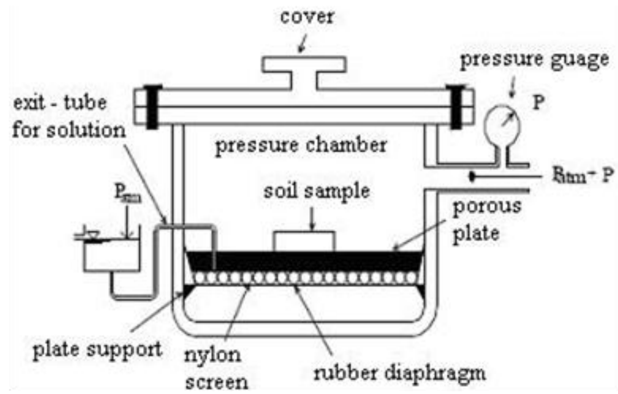


Figure 2. Richard´s Pressure Chamber.

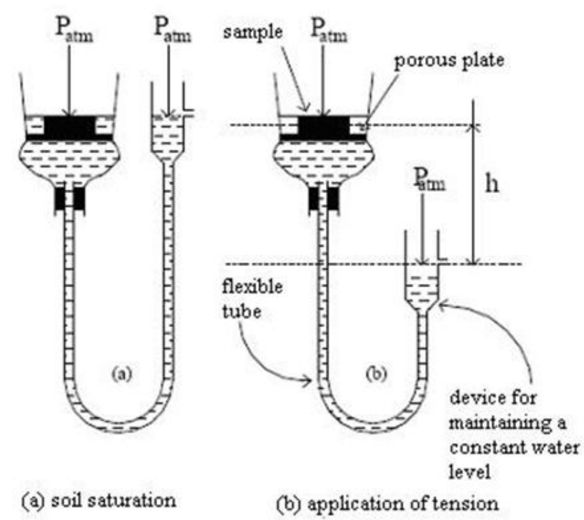


Figure 3. Illustration of Haines funnels equipment.

For Camapum de Carvalho & Leroueil (2004) (see also Feuerharmel et al., 2007) this “saddle” format in soil-water characteristic curve is typical of soils that present bi-modal porous distribution. This distribution is due to weathering processes that are responsible for the formation of soil particle aggregation. The comparison between the granulometric test results, with and without the use of deflocculant, indicated that in the soil studied, the clay particles tended to be presented as aggregated in their natural state.

Figure 5 shows similar behaviour of soil-water characteristic curves with “saddle” format also found in the mature granite residual soil from the research area 2, Cabo, Pernambuco (Lafayette, 2006). Futai et al. (2007) found similar results in a residual soil from Rio de Janeiro.

Coutinho et al. (2006) presents results from another Brazilian tropical soil from Pernambuco (Barreiras Formation). The soil-water characteristic curve was obtained through three procedures: the filter paper method, pressure membrane and vacuum desiccator. The tests were carried out in specimens molded directly in the block sample.

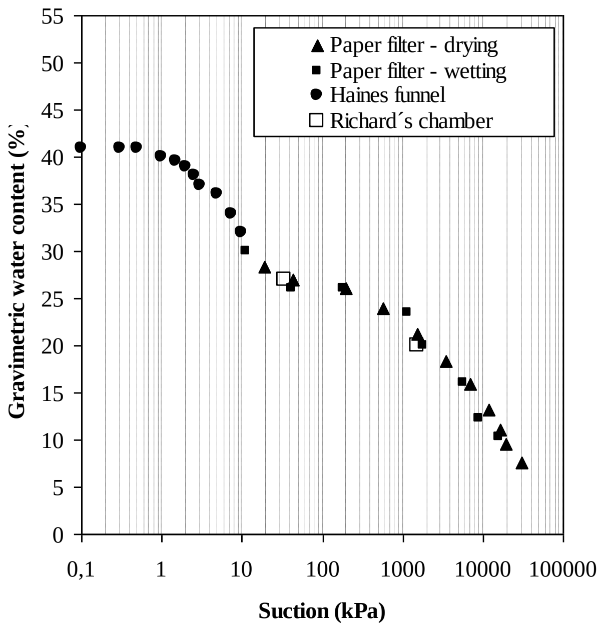


Figure 4. Soil-water characteristic curve research area 1 - Silva & Coutinho (2007).

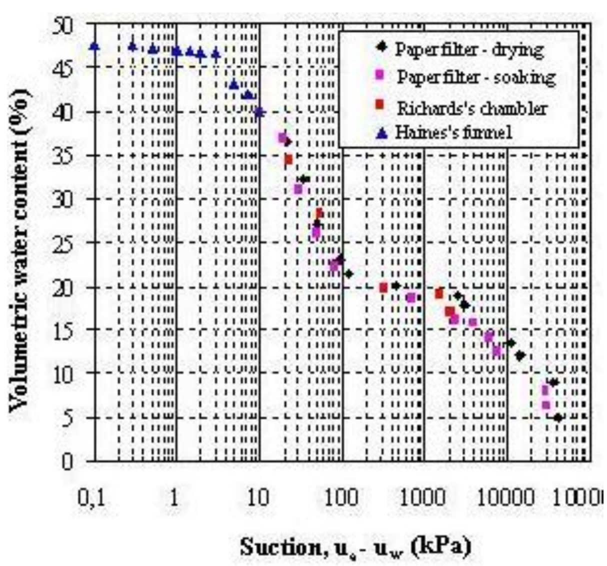


Figure 5. Soil water characteristic curve – area 2, Lafayette (2006).

Figure 6 presents the soil-water characteristic curve obtained, which was adjusted according to van Genutchen's model. For this case, it is observed that the soil presents a sandy soil typical curve characterized by the great variation in moisture content occurring in low suctions (from 1 to 10 kPa). In general, the three methods showed agreeing values of suction, without significant scattering of data. From the adjusted curve a suction value in the air entry at about 1 kPa. The residual volumetric moisture is 5.5%, corresponding to a suction about 8 kPa. These results suggest that a small variation in suction (between 1 and 10 kPa) may lead to great variation in soil behaviour, both from a mechanical and hydraulic point of view.

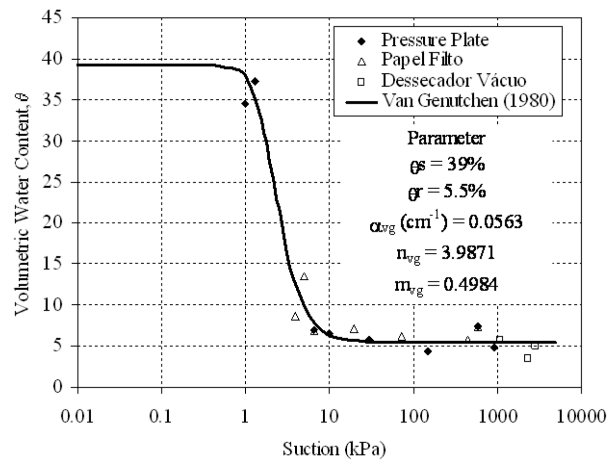


Figure 6. Soil-water characteristic curve adjusted by Van Genutchen (1980) – Barreiras Formation Coutinho et al. (2006).

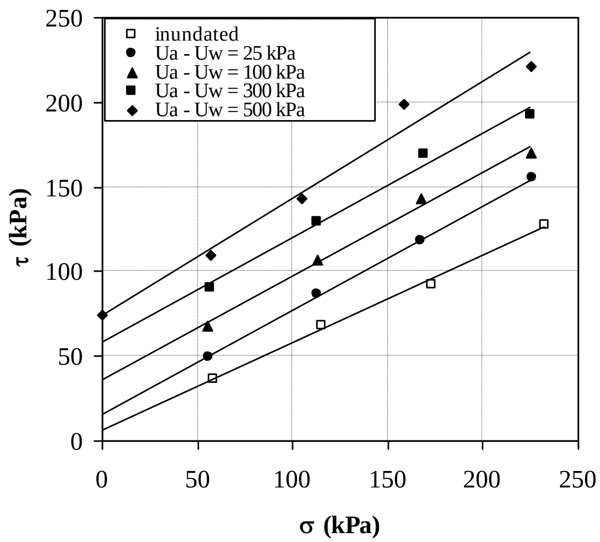
2.3 Direct shear tests with controlled suction

The equipment used consisted of a conventional press, adapted for use of a cell that allows the imposition and control of suction through the principle of translation of axes. The cell used in this research is identical to that described in Escário & Sáez (1986).

The suction is imposed to the soil by the difference between the air pressure supplied by hydrogen, applied through an air valve and the water column maintained in the reservoir fixed on top of the press. The tension is applied through a system hanging weights, identical to the conventional direct shear tests. The air pressure was applied only under the weight of charge transference plate and maintained during 10 days. The horizontal force was determined through a load ring. Samples were used, at dimensions of 50mm side and 22mm in height. The suctions adopted were 25, 100, 300 e 500kPa.

After this period (suction equilibrium) specific normal stress were applied, accompanying the deformations up to stabilization. The normal stress adopted were 50, 100, 150 e 200kPa, which were maintained for a minimum of 24 hours.

The shear strength envelopes in the plain (σ_v, τ) for the suction values of 25, 100, 300 e 500kPa are represented in Figure 7. The envelope considering suction of 0kPa, obtained through conventional direct shear tests in the submerged condition are also presented in this figure. It can be observed that the friction angles in general varied from 26.3° to 31.5°. The results indicated that the envelopes are linear, and in general, near to be parallel to each other (particularly with suction different of “zero”), as have been proposed in literature (Fredlund et al. 1978; Alonso et al. 1990; Wheeler & Sivakumar 1995; Ng & Chen, 2008).



(Ua–Uw)= 0kPa	c = 9,7kpa	$\phi = 26{,}3°$	R^2= 0,996
(Ua–Uw)~ 5kPa	c = 9,8kpa	$\phi = 29{,}2°$	R^2= 0,977
(Ua–Uw)= 25kPa	c = 15,4kpa	$\phi = 31{,}6°$	R^2= 0,999
(Ua–Uw)= 100kPa	c = 36,5kpa	$\phi = 31{,}3°$	R^2= 0,991
(Ua–Uw)= 300kPa	c = 58,7kpa	$\phi = 31{,}5°$	R^2= 0,987
(Ua–Uw)= 500kPa	c = 74,7kpa	$\phi = 34{,}4°$	R^2= 0,956

Figure 7. Shear strength envelopes for different values of suction – mature residual soil from Camaragibe.

For the granite residual soil from the research area 2 – Cabo the results were similar. However, the values for the friction angles were higher, varying from 31.5 (submerged) to practically constant and around 38° for suction between 20 to 500 kPa.

In the plain (s, τ) (Figure 8) a clear curvature is observed in the shear strength envelopes, which will result in the reduction of the ϕ_b parameter with the suction, according to what has been seen in various results in literature. In this plain the experimental results showed as being satisfactorily adjusted to the hyperbolic function presented by Gens (1993), presented in equation 1. Table 1 presents the parameters of hyperbolic adjustments for each vertical stress.

$$\Delta\tau_f = \tau_f - \tau_f^{sat} = \frac{s}{\cot g(\theta') + \frac{s}{c^*}} \quad [1]$$

Where: $s = u_a - u_w$ = suction matricial.

, [2] $$c^* = \frac{c_{máx}}{r}$$

where r is an adjusted parameter.

Results of literature (Fredlund et al., 1995 and Vanapalli et al., 1996) show that even the air entry value the soil strength increases linearly with the suction. From this value, the strength increases in a non linear way until the suction corresponding to residual water content, from which the increase in the strength becomes insignificant. Fredlund (2006) and Vilar (2007) present more recent results and discussion on this topic, including by Vilar an expedite method to predict the shear strength of unsaturated soils. The soil-water characteristic curve (Figure 4) relating to sample where shear tests, were carried out, with suction controlled, suggested air entry value in the order of 1kPa. This low suction value in the air entry value, justified the non linearity observed in the envelope in the plan (s, τ) (Figure 8). It is verified that the strength are still to be found elevated with the rise the suctions, suggesting that residual stage has still not been reached.

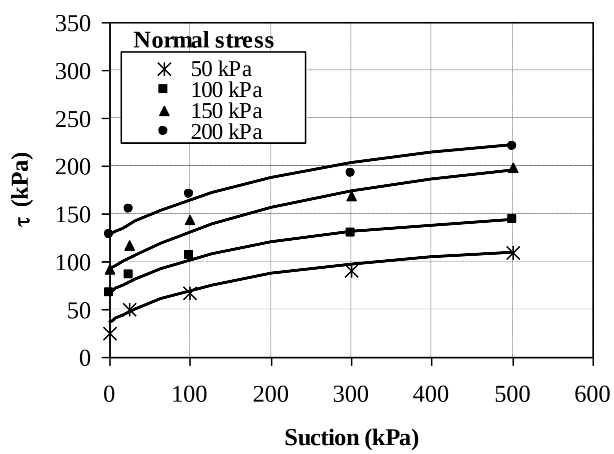


Figure 8. Shear strength envelopes in the space (s, τ) adjusted according to the hyperbolic function used by Gens (1993) – residual soil area 1.

Table 1. Parameters of adjustment of the hyperbolic function in Figure 8 for each normal stresses.

ϕ'(°)	σ_n (kPa)	τ^{sat} (kPa)	c^* (kPa)
	50	36,29	103,3
26,3	100	67,48	110,0
	150	92,22	179,0
	200	127,53	153,5

Figure 9 shows similar behaviour in the plain (s, τ) found in the mature granite residual soil from Cabo (research area 2) by Lafayette (2006). Futai et al. (2007) also found similar results in a residual soil from Rio de Janeiro.

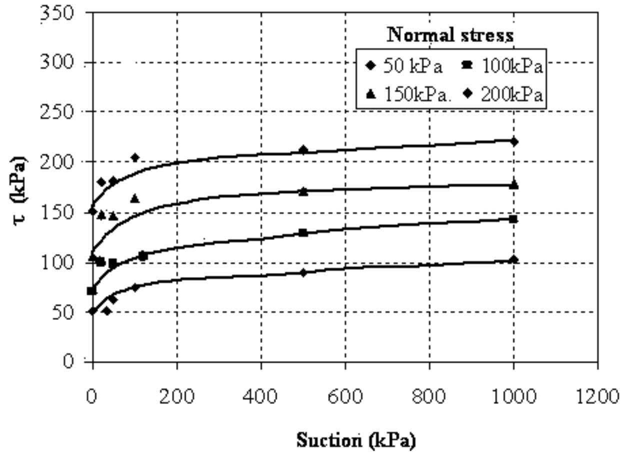


Figure 9. Shear strength envelopes in the space (s, τ) adjusted according to the hyperbolic function used by Gens (1993) –residual soil of granite – research area 2.

Figure 10 (Coutinho et al. 2006) presents the shear strength envelopes in the plane (σ_v, τ), at peak condition, with their corresponding strength parameters, for another tropical soil from Pernambuco (Barreiras Formation). Conventional and controlled suction direct shear tests were performed. The controlled suction tests were performed in suction of 30 kPa. The envelopes are linear and practically parallels. The friction angles (ϕ) obtained ranging between 35.7 and 37.2o, showing practically a same value for this case. The cohesion intercept (c) ranged between 7 to 20 kPa, presenting a slight increase (but consistent) with the decreasing of the moisture content (increasing with suction) as expected.

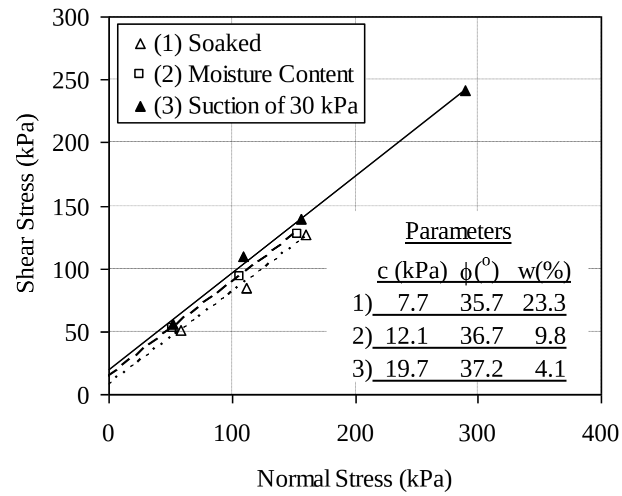


Figura 10. Shear strength envelopes – direct shear test, Barreiras Formation – Coutinho et al. (2006)

3 CONCLUSIONS

This paper presents results of a geotechnical characterization of two unsaturated mature granite residual soils from two areas of Recife Metropolitan Region, Pernambuco, Brazil. In these areas research were done due to the occurrence of landslide (city of Camaragibe) and erosion (city of Cabo) processes. Through the determination of the physical characterization, soil-water characteristic curve and shear strength with suction control it was possible to contribute to a better understanding of the behaviour in the unsaturated condition of these material. Granulometric tests indicated that the particles of clay in these soils are found to be aggregated in their natural state. The good results obtained for the soil water characteristic curve show that the three methods (filter paper, Haines funnel and Richard´s chamber), were considered adequate for determination of the entire curve (including the low suction values), indicating that these techniques should be used simultaneously and more frequently in geotechnical investigations. The format of the curve shows a “saddle” format which is typical of soils that present bi-modal porous distribution. The results obtained through the direct shear tests with controlled suction indicated that the envelopes in the plane (σ_v, τ) are linear, and in general, near to be parallel to each other (particularly with suction different of “zero”), as have been proposed in literature. In the plain (s, τ) a clear curvature was observed in the shear strength envelopes, which means reduction in the ϕ_b parameter with the suction. Satisfactory adjust was obtained using the hyperbolic function proposed by Gens (1993).

ACKNOWLEDGEMENTS

This paper is part of a research project PRONEX supported by Federal and State Government – MCT / CNPq and FACEPE. The authors would like to acknowledge the support.

REFERENCES

Alheiros, M. M. 1998. Riscos de Escorregamentos na Região Metropolitana do Recife. Tese de Doutorado em Geologia Sedimentar, UFBA, Salvador-BA (in Portuguese).

Alonso, E.E; Gens, A. & Josa, A. 1990. A construtive model for partially saturated soils. Geotechnique, vol. 40, n°3, 405-430.

Bastos, C. A. B. 1999. Estudo geotécnico sobre a erodibilidade de solos residuais não saturados. Tese de Doutorado, UFRGS, 296p (in Portuguese).

Camapum de Carvalho & Leroueil, S. 2004. Curva característica de sucção transformada. Solos e Rochas, Jornal ABMS, 27, (3), 231-242 (in Portuguese).

Coutinho, R. C.; Souza Neto, J. B.; Santos, L. M. & Lafayette, K.P.V. 2006. Geotechnical Characterization of an unsaturated soil in the Barreiras Formation, Pernambuco-Brazil. Unsaturated Soils of on Conference.

Escário, V. e Sáez, J. 1986. The shear strength of partly saturated soils. Geotechnique, V.36, nº 3, 453-456.

Feuerharmel, C., Gehling, W. Y. Y. & Bica, A. V. D. (2007). The Use of filter-paper and suction-plate methods for determining de soil-water characteristic curve of undisturbed colluviums soils. Geotechnical Journal, Vol. 29, Nº 5, 419-425.

Fredlund, D. G. 2006. Unsaturated Soil Mechanics in Engineering Practice. Journal Geotechnical and Geoenvironmental Engr., ASCE, v.132, 3, pp.286-321.

Fredlund, D.G.; Vanapalli, S.; Xing, A.; e Pufahl, D.E. 1995. Predicting the Shear Strength Function for Unsaturated Soils Using the Soil-Water Characteristic Curve. Proc. of the 1°st Internat. Confe. on Unsaturated Soils, Paris, France, p.63-69.

Fredlund, D. G.; Morgenstern, N. R.; Widger, R. A. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal, v.15, n.3, p.313-321.

Futai, M.M., Almeida, M.S.S. & Lacerda, W.A. 2007. The laboratory behaviour of a residual tropical soil. Characterisation and Engin. Properties of Natural Soils – Tan, Phoon, Hight & Leroueil (eds) Taylor & Francis, London, Vol. 4, pp. 2477-2505.

Gens, A. 1993. Shear strength. Unsaturated soils: Recent Developments and applications, Civil Engineering European Courses – Programe of Continuing Education, Barcelona.

Lafayette, K. P. V. 2006. Estudo geológico – geotécnico do processo erosivo em encostas no Parque Metropolitano Armando de Holanda Cavacalti – Cabo de Santo Agostinho / PE. Tese de Doutorado. UFPE. Engenharia Civil, Recife-PE (in Portuguese).

Marinho, F. A. M. 1995. Medição de sucção com método do papel filtro. Anais do Congr. Brasileiro de Mecânica dos solos e Engen. de Fundações, 10, Foz do Iguaçu, ABMS, p. 515-522 (in Portuguese).

Ng, C.W.W. & Chen, R. (2008). Recompacted, natural and in-situ properties of unsaturated decomposed geomaterials. Geotechnica and Geophysical Site Characterization. Taylor & francis, 117-138.

Silva, M.M. (2007). Geological and geotechnical characterization of a landslide in a slope from Camaragibe City, Pernambuco. PhD Thesis, Federal University of Pernambuco (in Portuguese).

Silva, M. M. & Coutinho, R. C. 2007. Caracterização geotécnica de um solo não saturado da Formação Barreiras envolvido num movimento de massa em Camaragibe – PE. VI Simp. Brasileiro de Solos Não Saturados, Bahia, v.1. .391 – 398 (in Portuguese).

Vanapalli, S. K.; Fredlund, D. G.; Pufahl, D. E. 1996. The influence of soil structure and stress history on the soil – water characteristic of a compacted tell". Geotechnique, 49. 143-159.

Vilar, O.M. 2007. An expedite method to predict the shear strength of unsaturated soils. Soils and Rocks, Int. Geotechnical and Geoenvironmental Journal, Vol. 30, N. 1, pp. 51-61.

Wheeler, S.J. & Sivakumar, V. 1995. An elasto-plastic critical state framework for unsaturated soil. Geotechnique, v.45, n°1, 35-53.