Tensile strength changes under drying and its correlations with total and matric suctions

Variation de la résistance à la traction due à la dessiccation et sa corrélation avec la succion matricielle et total

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ABSTRACT
Experimental evidences show that the effect of matric suction on stress and hence on shear and tensile strength of soil can be considerable, but limited in dry soils by the onset of cracking (Favaretti, 1995). In the present paper, several laboratory results, obtained by means of the Brazilian test are shown. Results of tensile strength of a soil were obtained using the diametral compression test, or Brazilian test, following the technique proposed by Krishnayya & Eisenstein (1974), Maciel (1991); Das et al. (1995) and Favaretti (1995). These tests consist of transversally compressing cylinders of soil throughout its generating line to cause them to fail by tensile throughout the diameter of the transversal section. Various tests were carried out on different levels of humidity and the results were correlated with the physical indexes. The samples were prepared in the laboratory from slurry condition, saturated with two different fluids. Their moisture retention curves were also determined. It was verified a high level of osmotic suction, which allowed to analyze separately the influence of the matric and total suction in the tensile strength behavior. It was observed that the total suction seems to control the soil tensile strength rather than the matric suction.

RÉSUMÉ
Preuves expérimentales montrent que l'effet de succion intergranulaire sur le stress et, par conséquent, sur la résistance à la traction et au cisaillement des sols peuvent être considérables, mais limitées dans les sols secs par l'apparition de fissures (Favaretti, 1995). Dans le présent document, plusieurs résultats de tests de laboratoire, obtenu au moyen de l'essai sont indiqués brésilienne, en essayant de vérifier cette information. Résultats de la résistance à la traction d'un sol ont été obtenues en utilisant la compression diamétralement test, ou test du Brésil, selon la technique proposée par Krishnayya et Eisenstein (1974), Maciel (1991), Das et al. (1995) et Favaretti (1995). Ces tests consistent en la compression du cylindre transversal des sols tout au long de sa génératrice de les provoquer à l'échec par traction à travers le diamètre de la section transversale. Divers tests ont été effectués à différents niveaux de l'humidité et les résultats peuvent être corrélés avec les indices physiques Les échantillons ont été préparés dans le laboratoire et saturé avec deux différents types de fluides. Les courbes de rétention de l'humidité ont également été déterminées. Il a été vérifié un niveau élevé de succion osmotique, ce qui a permis d'analyser séparément l'influence de la succion matricielle et total dans la résistance à la traction des sols.

Keywords: tensile strength, laboratory tests, Brazilian test, total and matric suction

1 INTRODUCTION

In a general way, it has been admitted that the soil tensile strength is very low when compared to its compression or shear strength. Because of this, little attention has been given to study the mechanisms that control soil behavior in relation to tensile forces. However, with the growth of studies in unsaturated soils in search of a better understanding of drying and fissuring processes, more attention is being given to this type of mechanism, especially for researchers in the areas of Soil Physics and Agronomy. It has been recognized that for a complete understanding of the full drying process of a soil, which culminates invariably with its cracking, it is necessary to study its tensile strength and its relation to moisture content and degree of saturation. The fracturing of a soil during the drying process will occur presumably when attraction forces between particles, which are likely to increase with suction, overcomes the tensile strength in the soil. This tensile strength, in turn, would be a result, among other factors, of physical-chemical bonds acting between soil particles. These bonds probably increase during the drying process up to when the whole structure is affected by cracks, which reduce the tensile strength of the soil mass (Favaretti, 1995).

This paper presents results of tensile strength of a soil obtained using the diametral compression test, or Brazilian test, following the technique proposed by Krishnayya & Eisenstein (1974), Maciel (1991); Das et al. (1995) and Favaretti (1995). These tests consist of transversally compressing cylinders of soil throughout its generating line, in order to provoke failure by traction throughout the diameter of the sample transversal section. The samples were prepared in the laboratory and saturated with two types of different fluids. Various tests were carried outs on different levels of moisture content and the results were correlated with the physical indexes. Moisture retention curves were also determined. It was verified a high level of osmotic suction which allowed to separately analyze the influence of the matric and total suction upon the tensile strength.

2 MEASUREMENT OF TENSILE STRENGTH OF SOILS

In a general way, laboratory tests for the evaluation of the tensile strength in soils are divided into two types: direct and indirect methods. Direct methods are those that effectively submit the soil to traction, measuring directly the strength value.

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Indirect methods use the application of other types of force and the tensile strength is obtained indirectly by interpretation of the testing results. In this group is the diametral compression test or the Brazilian test. In general, the tensile strength in soils and rocks has been determined by the Brazilian Test. A standard procedure for this type of test has been put forwards by ASTM (D 3967-95a). Compression forces are applied on thin cylindrical samples (thickness or height h and diameter d), using two rigid parallel plates, one opposite to the other. As shown in Figure 1, rupture occurs along the diametric vertical plane connecting the two loaded sides.

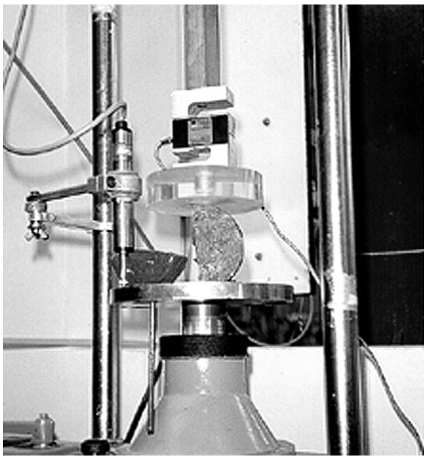

Figure 1. View of a sample showing rupture along the diametric vertical plane after testing

The tensile strength can be evaluated by the following formula (Das et al., 1995; Krishhnayya & Eisenstein, 1974):

$$\sigma_t = \frac{2P}{\pi d h} \quad (L^{-1}MT^{-2}) \qquad (1)$$

where: P is the maximum vertical load applied in the test; d is the diameter of the sample and h, its thickness or height. Krishhnayya & Eisenstein (1974) alerted that this is a not an adequate relation for soils that have a large difference between the elasticity modules in compression and traction loading.

3 MATERIALS AND METHODS

3.1 *Tested Material*

The tests were carried out on samples prepared in the laboratory. The soil was initially homogenized in the form of mud and consolidated by self weight. After that, it was exposed to dry to form a single and homogenous layer. Once the desired moisture content was reached, cylindrical samples were molded from the reconstituted material. This preparation procedure guaranteed that all samples were in a normally consolidated condition. Moisture retention curves and the drying curves were also obtained following the same conditions; refer to Villar (2002) for details.

Two different fluids were used to saturate the samples. One of them was caustic soda, with a pH of around 13, and the other, a mixture of caustic soda and sulfuric acid, with a pH of around 8. Therefore, there were two types of tested samples, both with the same grain size distribution and formation sequence, but with different pore fluids. These two different samples were called neutralized soil and non neutralized soil, respectively. As a consequence of the use of these liquids, the generated osmotic suction throughout the drying process was high. Therefore, the matric and total suction values were distinct and it was possible to verify the relation among the tensile strength values with each of them separately. Basic geotechnical characteristics of the tested soils are summarized in Table 1. In this table, all the results were obtained using the industrial fluids instead of water.

Table 1. Geotechnical characteristics of tested soils

GRAIN SIZE DISTRIBUTION (NBR 6502/95)						
Material	Using water as dispersant (%)			Using industrial fluid as dispersant (%)		
	sand	silt	clay	sand	silt	clay
Neutralized soil	0	49	51	62	30	8
Non neutralized soil	0	78	32	57	40	3
SOLID SPECIFIC GRAVITY (NBR 6508/84)						
Material	>#60	> #100	> #200	< #200	Integr.	
Neutralized soil	3,49	3,49	3,51	3,54	3,39	
Non neutralized soil	3,53	3,60	3,54	3,54	3,55	
ATTERBERG LIMITS (NBR 6459 and 7180/84)						
Material	<#40			Integral (drying path)		
	w_L	w_P	PI	w_L	w_P	PI
Neutralized soil	33,4	27	6,3	48,8	34	14,8
Non neutralized soil	33,9	26,8	7	63,6	29,3	34,3

where: w_L = liquid limit; w_P = plasticity limit; PI = plasticity index

3.2 *Test methodology*

In this work, the procedures and methodology described by Maciel (1991) was adopted. The samples were of 76mm in diameter by 20mm of thickness, molded from normally consolidated soils, initially saturated and then air dried. Only those samples without cracks originated from the drying process were used. They were vertically compressed in a test machine using a constant rate of strain. The vertical load and vertical displacement were measured using a load cell and a displacement transducer. In the extremity of the load cell, an acrylic plate was adapted, promoting the distribution of the load in the soil within a narrow band. The testing rate (2mm/min) was the same used by Maciel (1991). Such velocity was chosen to minimize changes in moisture content in the whole sample during testing.

4 TEST RESULTS

The relationships between the tensile strength, the volumetric moisture content and the degree of saturation obtained for the soil initially saturated with the neutralized fluid are shown in Figures 2 and 3. It was verified the occurrence of a linear relationship between the tensile strength and these physical indexes for moisture contents higher than the plasticity limit. The resistance goes towards zero as the soil approaches saturation (see Figure 2). This suggests that the tensile strength develops as a consequence of the drying process.

As the material becomes unsaturated, after a determined value of these physical indexes, which in terms of degree of saturation corresponds to the point of 86%, a pronounced drop was registered in the resistance. Shortly after the shrinkage limit, the resistance increases again until after reaching the minimum voids ratio of the soil. The second peak occurred for a gravimetric moisture content of 4% (S = 14%). From then on, the tensile strength fell again in the semi log scales of Figures 2 and 3.

To explain this behavior, the drying curve, that is the relation between voids ratio and gravimetric moisture content of the soil, was analyzed. This curve, shown in Figure 4, can be divided into three regions. The region of *normal shrinkage* is characterized by the fact that the contracted soil volume is equal to the volume of evaporated fluid. In this region, the soil is saturated and a linear relationship is obtained. The following area, called *residual shrinkage*, shows a reduction in the rate of soil volume contraction, implying in an increase of air volume that substitutes the removed liquid. The last area of the graph, denominated *zero shrinkage*, is that where the soil does not vary anymore in volume, having reached its minimum void ratio.

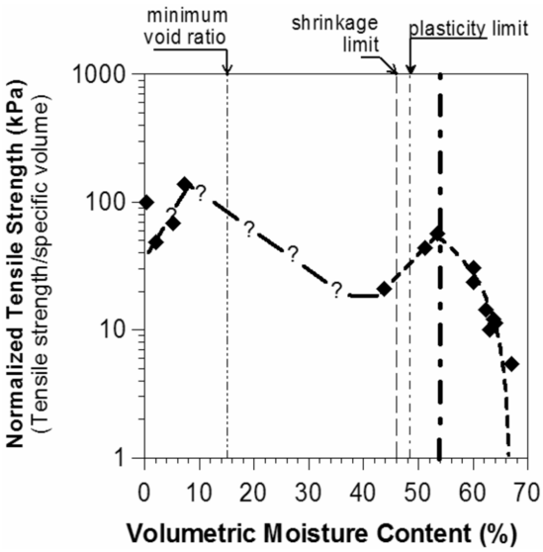

Figure 2. Normalized tensile strength against volumetric moisture content of the neutralized soil.

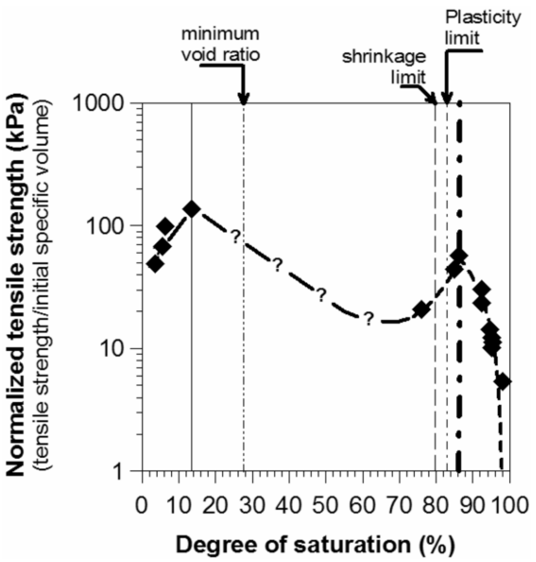

Figure 3. Normalized tensile strength and degree of saturation of the neutralized soil

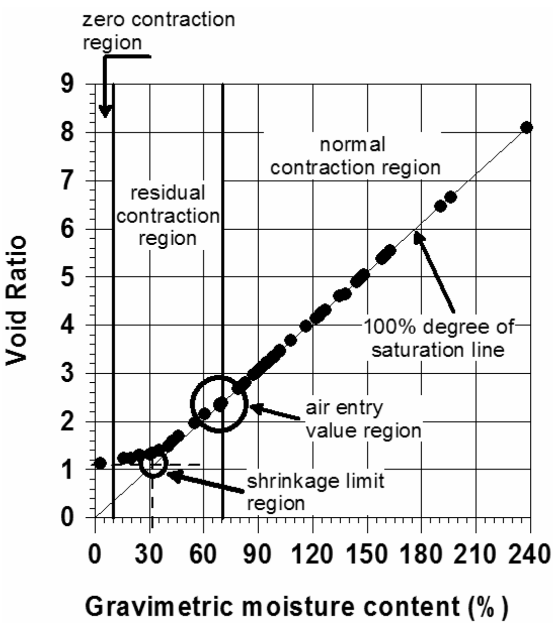

Figure 4. Drying curve of the neutralized soil

At a gravimetric moisture content of 40% the drying curve starts to distance more from the straight saturation line. This point corresponds to those in Figures 1 and 2 where the tensile strength starts to drop. That is, when there is air in the sample, probably establishing a condition of continuous air inside the soil, a change in the evolution pattern of tensile strength occurs as the soil dries. To check this trend, a relationship between normalized tensile strength and suction was obtained. The result for the neutralized soil is shown in Figure 5. It was found a linear relationship between the normalized tensile strength and both matric and total suction up to a degree of saturation of circa to 86%. In the soil moisture retention curve, this degree of saturation corresponds to the point where the curve of total suction presents its maximum curvature, refer to Figure 6. That is, the tensile strength of the soil showed a sharp change in behavior at the point where the total suction of the soil also changed. Furthermore, the point where the second strength peak occurred (14% of degree of saturation) corresponds to the point where there is a new change in the trend of the total suction curve, which starts to enter the residual area. These results indicate, therefore, that total suction governs the soil response in relation to the tensile strength. This is in agreement with what was found by Tang et al. (1999), but other researchers such as Heibrock et al (2003) and Zeh & Witt (2005) affirmed that the tensile strength is just a function of the matric suction.

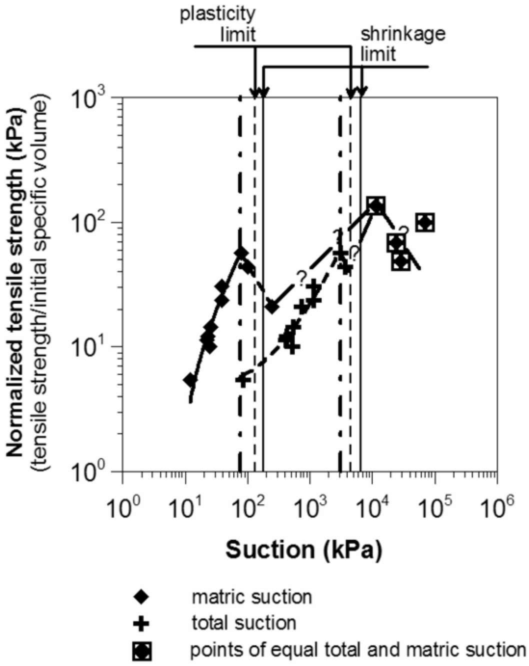

Figure 5. Normalized tensile strength and suction of the neutralized soil

It was decided to confirm the previously observed trend using a value that would be equivalent to the "energy" necessary to cause the rupture of the sample. For energy, it is being called the area under the curve of the external applied force plotted against vertical displacement. Similar analysis was done by Munkholm & Kay (2002). Figure 7 shows the relation between the "energy" and suction, showing that the "energy" is constant after the shrinkage limit until reaching the minimum void ratio, which corresponds to the region of minimum variation of the total suction.

The same type of analysis was performed for the non-neutralized soil. The two materials exhibit the same general behavior in terms of strength variation with the moisture content. Differences between these two materials are essentially numerical. They start to appear when they lose saturation. The difference increases when the degree of saturation reaches a value of around 80%, that is, when the non neutralized soil starts to have continuous air in the samples. The second peak occurs around 18%, which is equivalent to a saturation degree of 62%, much higher than in the case of the neutralized soil (14% of saturation). The behavior of the non-neutralized soil in terms of "energy" expended to cause rupture was also similar to that of the neutralized soil. That is, while the total suction remains constant, this "energy" did so as well.

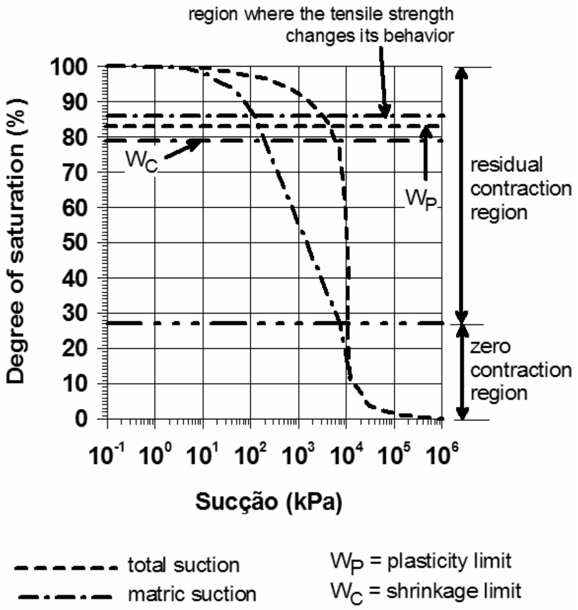

Figure 6. Moisture retention curve of the neutralized soil.

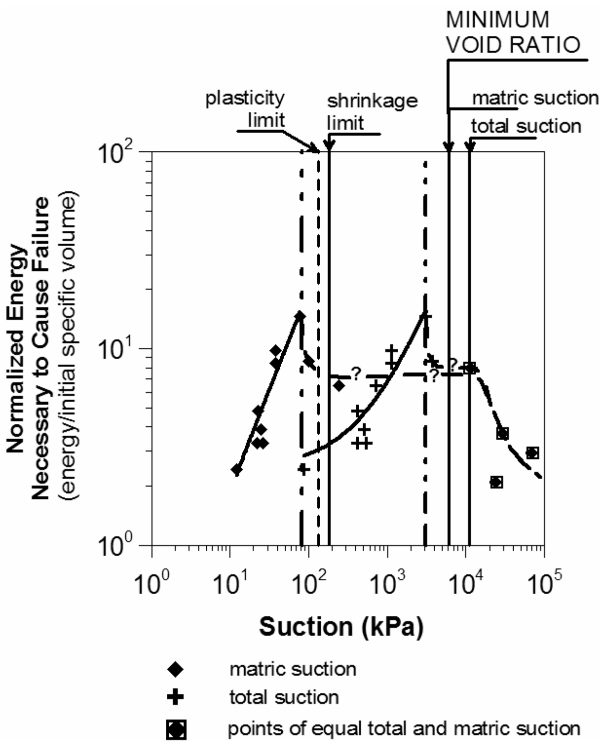

Figure 7. Suction and energy expended during the tensile test of the neutralized soil

5 CONCLUSIONS

This paper presented tensile strength values of a soil obtained using the diametral compression test, or Brazilian test. Tests were carried out on samples with different moisture contents and the results of tensile strength could be correlated with soil physical indexes and with total and matric suctions. The samples were prepared in laboratory, being saturated with two different types of fluids. Moisture retention curves indicated a high level of osmotic suction for the material prepared with fluids with pH 14 and 8. This allowed for a distinct analysis of the effect of total and matrix suction. From the results obtained, it could be observed that:

1. In the relationship between tensile strength and physical indexes, both soils showed a change in behavior for a degree of saturation around 85%.
2. Considering the drying curves, it was verified that the point where this change in behavior occurred corresponds to the point where the drying curve starts to depart from the 100% saturation line.
3. For both soils, the tensile strength showed changes in behavior at moisture contents where the total suction also changed. Therefore, the obtained results indicate that total suction would govern the response of the soil in relation to the tensile strength (if the total suction changes, the tensile strength changes). Such finding was confirmed by analysis in terms of the "energy" necessary to cause rupture of the samples. When total suction stayed approximately constant, the "energy" also showed practically no variation

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