Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2347

Suction-controlled tensile strength of compacted clays

Résistance à la traction d'argile condensée contrôler par la succion

R.M. Zeh & K.J. Witt
Geotechnical Engineering, Bauhaus-University Weimar, Germany

ABSTRACT
This paper represents a testing method to directly measure the suction-controlled tensile strength of compacted clays under a constant, initial soil structure. Test results of a medium plasticity clay are shown as an example. The induced suction is 0 to about 140,000 kN/m². The tensile strength of the compacted clay reaches about 450 kN/m² as a maximum. In addition, analytic calculations based on the capillary theory show values in the same magnitude but underestimate the test results.

RÉSUMÉ
L'article exprime une méthode d'essaie directe pour déterminer la résistance à la traction d'argile condensée avec une constante structure de sol initial contrôlée par la succion. Le résultat d'essaie pour une argile avec une plasticité moyenne est affichée comme une exemple. La succion induite est entre 0 et approximativement 140,000 kN/m². La résistance à la traction d'argile condensée atteint approximativement 450 kN/m² maximum. De plus, les calculs analytiques basés sur la théorie capillaire montrent des valeurs dans la même ampleur, mais sous-estiment les résultats d'essais.

1 INTRODUCTION

The tensile strength of soils is usually not taken into account when solving typical geotechnical problems. The tensile strength plays an important role in connection with the examination of compacted clays' cracking in landfill liners or in cores of dam embankments, the calculation of slope stability or failure by heave in clayey soils.

Cracks in landfill liners or dam cores often arise from the reduction of the water content which is caused by desiccation. Furthermore, their permeability increases exceedingly (e. g. Albrecht & Benson, 2001, Heibrock, 1997). The main criteria of the initiation of cracks is, apart from the cover load and the soil structure, the tensile strength of cohesive soils linked with suction and the water content / degree of saturation / consistency, respectively (e. g. Heibrock et al., 2003, Meißner & Wendling, 1998, Morris et al., 1992).

The tensile strength (of soils) has relatively often been analysed in literature (e. g. Tang & Graham, 2000, Snyder & Miller, 1985, Ajaz & Parry, 1975, Farrell et al., 1967 etc.), but the boundary conditions, such as density, soil structure etc., were often unequal. In addition, the testing methods varied, too (e. g. direct and indirect tensile strength tests, horizontal or vertical strain etc.).

In this paper, a method to measure the direct tensile strength of compacted clays - under constant initial soil structure by varying suctions - is described. In addition, a few information on soil structure, typical test results and analytic approaches to calculate the tensile strength are represented.

2 SOIL STRUCTURE

It is known that the engineering properties of fine grained (clayey) soils are closely related to the soil water interaction (e. g. Mitchell, 1993, Nagaraj & Miura, 2001). A number of investigations indicated that the amount of water absorbed by the clayey soils (clay aggregates and particles) correlates to other properties of the soil, like shear strength, compressibility etc.

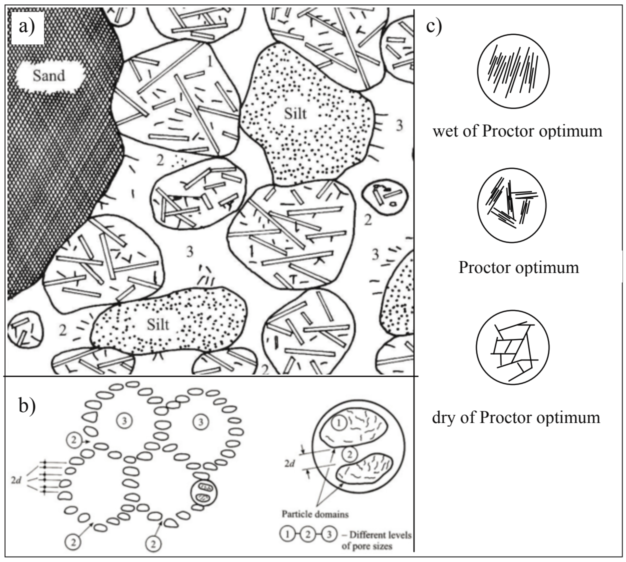

Figure 1. a) fine grained soil structure – 1: intra-aggregate pores, 2 (3): inter-aggregate (large enclosed) pores, b) possible micro fabric of clays (modified from Nagaraj & Miura, 2001), c) clay particles' orientation

Fig. 1a shows a schematic drawing of a typical structure of fine grained soils – sand, silt, clay aggregates (clusters) and pores with different sizes. The clay aggregates (e. g. Fig. 1b) are consist of clay particles which are formed by face to face (parallel), edge to edge (normal) or mixed orientations – size between 0.01 to 1 µm. The orientation depends on the clay type, water content, soil preparation etc. Clays compacted wet of Proctor optimum naturally have a dispersed structure (parallel) - with small inter-aggregate pores, compacted dry of Proctor optimum a meta-stable flocculated structure (normal) - with larger and more inter-aggregate pores - and compacted at Proctor optimum a mixture of both structures (Fig. 1c). Therefore, the number, the size of pores and aggregates are strongly influenced by the conditions during compaction.

Depending on the definition of pores (confer e. g. Diamond, 1971, Nagaraj & Miura, 2001, Heibock et al. 2003, Cuisinier &

Laloui, 2003), intra-aggregate pores (1 in Fig. 1a) have a maximum diameter of 0.002 to 0.01 µm. The size of the inter-aggregate pores is 0.01 to 0.1 for the small ones, large enclosed pores are up to 10 µm (2 and 3 in Fig. 1a).

The water trapped in intra-aggregate pores is predominatly influenced by particle surface forces. The inter-aggregate pore water is dominated by capillary forces.

As a result of the soil structure described above, analytic tensile strength calculations may use some approaches of the capillary theory of porous media (see chapter 6). For this purpose, the clay aggregates are regarded as single soil particles of the same size and shape.

3 SAMPLE PREPARATION AND TEST PROCEDURE

The samples were made in a Proctor mould at constant conditions for each series (3 layers, 25 blows, standard hammer, 100 % Proctor optimum or 97 % wet / dry of Proctor optimum) which created a cylinder of 150 x 120 mm. Therefore, the initial soil structure per series was always the same. Then the cylinder was cut in 3 slices which were individually prepared to hollow cylinders of 90 x 24 mm (inner diameter 8 mm) by carefully trimming the slices and drilling a hole. After that, the hollow-cylindric samples were stored for about 48 h to get homogenious conditions, then they were slowly dried or wetted until targeted water content value (or coressponding suction) was achieved. Besides, the samples were weighed and got a wax coating to measure the sample volume by dip-weighing. The center of the inner hole was later filled with a filter textile and in both sample ends a modified dowel was glued with epoxy resin. In the end, two small hooks, drilled in the dowels, were used to implement the tensile forces.

The tensile strength tests were run in a modified triaxial apparatus by measuring the tensile force and the strain. The samples were always torn apart with v = 0.001 mm/s until rupture occured. After that, the samples were examined where the crack run (almost always in the middle of the sample). Besides, the water content of the rupture zone and of the samples' end were measured.

The preparation and procedure described above was based on a modified method of Heibrock et al. (2003).

The shrinkage tests were conducted at small cylindric samples which were produced at the desired Proctor density (and water content), stored to homogenize and then left to dry slowly. After that, the volume of the samples and the water content were determined by dip-weighing and oven-dried method, respectively.

The 'water content – suction points' to fit soil-water characteristic curves (SWCC) were obtained by soil suction measurements with the axis-translation technique (e. g. Fredlund & Rahardjo, 1993, Likos & Lu, 2004) and the chilled-mirror hygrometer (CMH) technique (e. g. Leong et al., 2003, Likos & Lu, 2004). As a modification of the axis-translation technique, the porous filter stones were replaced with porous foils beyond 1,500 kN/m² suction.

The samples (axis-transl.-techn.) to determine the SWCC were Proctor compacted, saturated and then dewatered to an equilibrium by different pressure stages. The similar produced samples of the CMH tests were directly dried and measured after storing.

4 MATERIAL PARAMETERS

In this paper, the authors present results of one soil, a medium plasticity clay called Plessa (Pl). The soil parameters are shown in Table 1. The soil has no active clay minerals.

To convert the water contents into suction values shrinkage curves and soil-water characteristic curves (SWCC) were necessary. A shrinkage curve (void ration versus vol. water content) of the clay Plessa, compacted at Proctor optimum (Pl100o), is shown in Fig. 2. As a comparison, indirect results of the tensile strength tests are integrated in the figure.

The axis-translation technique and CMH measurements could be directly used because of the non-active clay minerals (i. e. no osmotic suction) in the clay Plessa. Therefore, the matric and total suction (CMH) is equal. To get consistent volumetric water content values in both procedures described, the water content values were recalculated by using the shrinkage curves (cf. Fredlund & Rahardjo, 1993, chapter 13).

Table 1. Soil parameters of clay Plessa (Pl)

Parameters		Values
clay content		41,1 %
silt content		58,3 %
sand content		0,6 %
organic loss V_{Gl}		4,5 %
liquid limit w_l		44,9 %
plastic limit w_p		21,4 %
plasticity index I_p		23,5 %
consistency index I_c		0,94
water adsorption w_a		94,0 %
specific gravity ρ_s		2,676 g/cm³
Proctor density:	Proctor optimum	1,65 g/cm³
	optimum water content	21,0 %
	97 % of Proctor optimum	1,60 g/cm³
	water content	16,6 % / 24,4 %
permeability $k_{f,\,sat}$		8,1 E-11 m/s
shear strength φ'		25,0°
cohesion c'		16,8 kN/m²

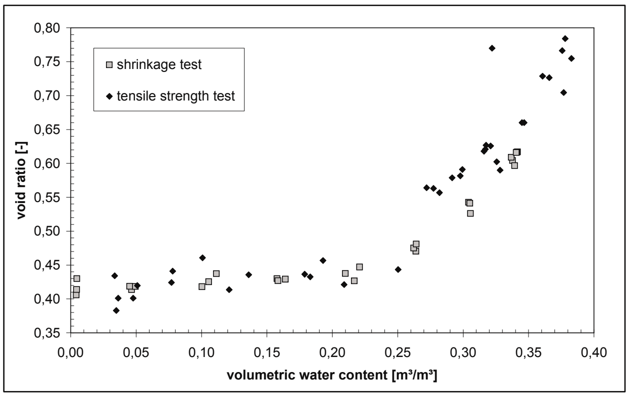

Figure 2. Shrinkage curve of clay Plessa (Pl100o)

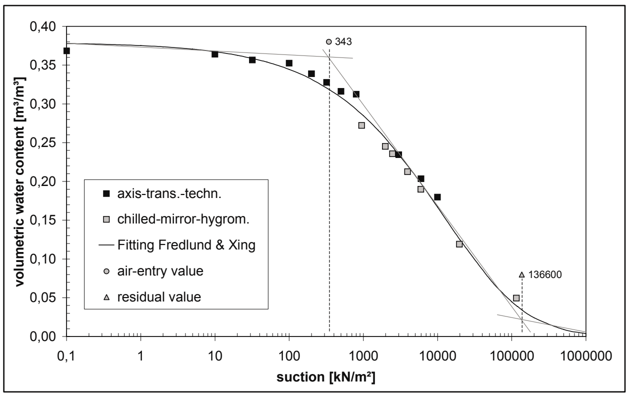

Figure 3. Soil-water characteristic curve of clay Plessa (Pl100o), fitted with Fredlund & Xing (1994)

Fig. 3 represents the SWCC of the clay Plessa, Proctor compacted (Pl100o), with a fitting curve by Fredlund & Xing (1994) and the air-entry and residual values of 343 and 136,600 kN/m², respectively.

5 TENSILE STRENGTH TEST RESULTS

Figures 4 to 6 represent the results of the tensile strength tests for the samples of clay Plessa - compacted at Proctor optimum (Pl100o) - relating to the suction, the degree of saturation and the consistency.

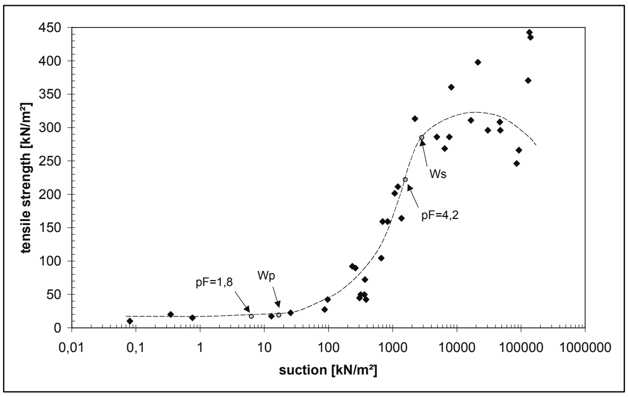

Figure 4. Tensile strength versus suction (Pl100o)

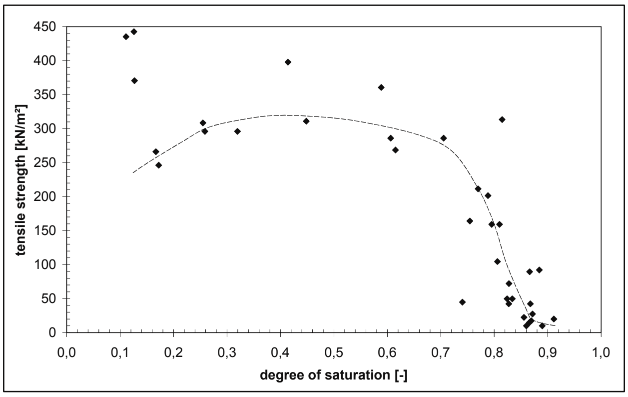

Figure 5. Tensile strength versus degree of saturation (Pl100o)

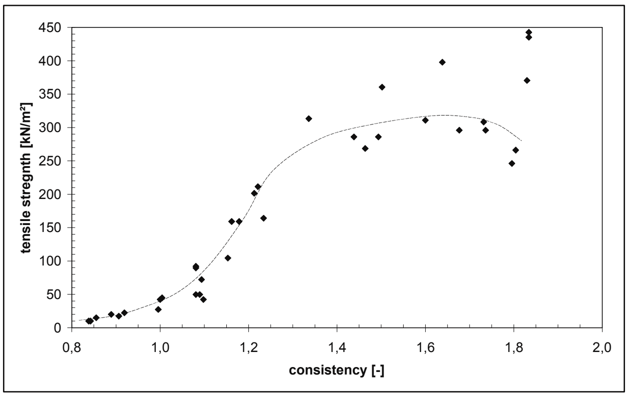

Figure 6. Tensile strength versus consistency (Pl100o)

The tendency is relatively clear up to suction values of 5,000 kN/m². Beyond this suction, values are more scattered but show an increase up to a peak at a suction of about 16,000 kN/m², afterwards there is a slight decrease. The suction results higher than 100,000 kN/m² have to be considered critically because of further effects besides capillarity (cf. Fig. 4). Figures 5 and 6 represent similar results.

Figure 4 also shows typical soil mechanical or soil physical values – shrinkage (Ws) and plastic limit (Wp) or welting point (pF=4.2) and field capacity (pF=1.8).

6 CALCULATIONS AND COMPARISONS

As described in chapter 2, the clay aggregates can be regarded as homogenous soil particles of the same size and shape. Therefore, the capillary theory of porous media can be used to calculate the tensile strength (Molenkamp & Nazemi, 2003, Heibrock et al., 2003).

Schubert et al. (1975) and Schubert (1982) described different soil-water stages (capillary, transition and pendular state) and showed approaches to calculate the forces between different contact forms (smooth spheres, faces etc.). The calculations are based on the simplified geometry of toroidal water lenses as water bridges. Molenkamp & Nazemi (2003) represented similar approaches for rough spheres with non-toroidal water lenses.

The procedure at Schubert's calculations is to get a dimensionless suction for a specific suction and particle diameter. With this value the bridge angle has to be read from a first diagram, then the dimensionless contact force from a second one. After converting this force and considering the grain size distribution and the void ratio (Schubert et al., 1975) of the soil, a tensile strength can be calculated. The procedure of Molenkamp & Nazemi (2003) is very similar (cf. the procedures at Heibrock et al., 2003).

Figure 7 represents calculation results of identical sphere to sphere (s-s) and sphere to face (s-f) contact forms at a distance of S=a/x=0.001 by considering only the pendular state. The comparison shows that the calculated tensile strengths have the same magnitude like the test results and represent a similar development of the values, but underestimate them. Better results could be estimated by considering smaller grain sizes and more face to face contact forms in the soil structure (Heibrock et al., 2003). In addition, forces based on the suction and the degree of saturation in the inter-aggregate pores should also be considered (cf. Schubert et al., 1975) in the transition state. They would directly increase the tensile strength values. However, they are difficult to collect.

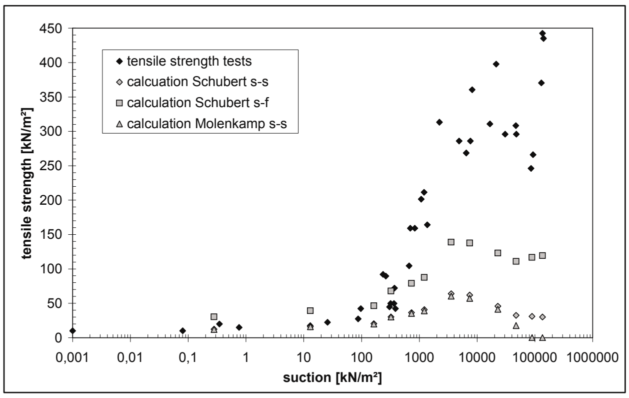

Figure 7. Comparison of tensile strength test results and calculated tensile strengths (capillary theory)

A good description of the tensile strength procedure also gives the following equation

$$t = a + b \cdot \exp^{(-0{,}5(\ln(\frac{s}{c})/d)^2)} \qquad (1)$$

where t is the tensile strength and s the suction, a, b, c and d are fitting parameters.

Figure 8 shows a comparison of the modified test results (without values higher than 100,000 kN/m²) and the equation (1) where a = 10.349, b = 331.214, c = 15,388.920 and d = 2.187 produced the best fit (r^2 = 0.942).

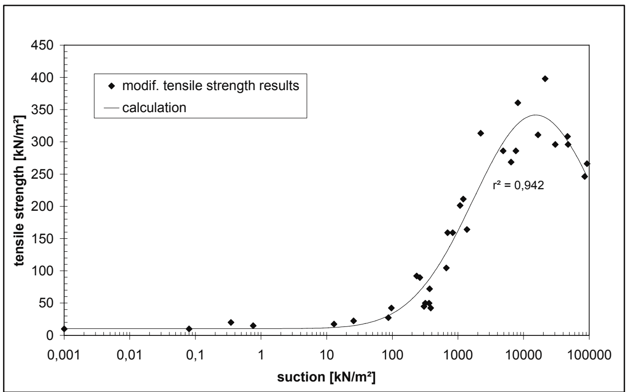

Figure 8. Comparison of modified tensile strength test results and calculated tensile strengths (best fit of equation 1)

7 CONCLUSIONS

The presented direct test method is very appropriate for examining the tensile strength of compacted clays (or fine grained soils) exposed to different suctions (water contents). It is also possible to test fetched in-situ samples, too. The results clearly show the dependency on the soil-water interactions by increasing up to a peak value and a slight decrease afterwards. These tendencies have to be verified by further soils and soil structures, respectively. The analytic calculations which are simple for the time being and which are based on capillary theory approaches at the pendular state have a similar magnitude of tensile strength, but underestimate the tensile strengths attained in the laboratory tests. By involving e. g. capillary-based tensile strength parts in the transition state or smaller grain sizes, improved results can be expected.

The better understanding of suction-controlled tensile strength developments of compacted clays can be used to improve the risk assessment of suction-induced cracks of clay liners. Therefore, numerical calculations of the water balance or water transport in multi-layered soil systems have to be installed to design improved liner systems of landfills etc. Furthermore, the knowledge of the suction-controlled tensile strength combined with in-situ monitoring systems of suction can also act as an early-warning system.

ACKNOWLEDGEMENTS

The authors gratitude Mrs. Appel, Mrs. Hagner and Mr. Kämmer, who did part of the experimental works at the ‘Laboratory of the Material, Research and Testing Institute’ MFPA, Weimar, under the management of Mr. K. Lemke.

REFERENCES

Ajaz, A., Parry, R. H. G. 1975. Stress-strain behaviour of two compacted clays in tension and compression. *Géotechnique*, Vol. 25, No. 3, pp. 495 – 512

Albrecht, B. A., Benson, C. H. 2001. Effect of desiccation on compacted natural clays. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 1, pp. 67 – 75

Cuisinier, O., Laloui, L. 2003. Fabric Evolution of an Unsaturated Compacted Soil during Hydromechanical Loading. in SCHANZ (ed.) 2004. Unsaturated Soils: Experimental Studies. Proceedings of the International Conference ‘From Experimental Evidence towards Numerical Modelling of Unsaturated Soils’, Weimar, Germany, September 18 – 19, 2003, Volume I, *Springer Proceedings in Physics* 93, Springer, Berlin, pp. 147 – 158

Diamond, S. 1971. Microstructure and pore structure of impact compacted clays. *Clays and Clay minerals*, Vol. 19, pp. 239 – 249

Farrell, D. A., Greacen, E. L., Larson, W. E. 1967. The Effect of Water Content on Axial Strain in a Loam Soil Under Tension and Compression. *Soil Sci. Soc. Amer. Proc.*, Vol. 31, pp. 442 – 450

Fredlund, D. G., Xing, A. 1994. Equations for the soil-water characteristic curve. *Can. Geotech. J.*, Vol. 31, No. 3, pp. 521 – 532

Fredlund, D. G., Rahardjo, H. 1993. *Soil Mechanics for Unsaturated Soils*. John Wiley & Sons, New York

Heibrock, G., Zeh, R. M., Witt, K. J. 2003: Tensile strength of compacted clays. in SCHANZ (ed.) 2004. Unsaturated Soils: Experimental Studies. Proceedings of the International Conference ‘From Experimental Evidence towards Numerical Modelling of Unsaturated Soils’, Weimar, Germany, September 18 – 19, 2003, Volume I, *Springer Proceedings in Physics* 93, Springer, Berlin, pp. 395 – 412

Heibrock, G. 1997. Desiccation cracking of mineral sealing liners. in CHRISTENSEN, COSSU & STEGMANN (eds): *Proceedings Sardinia 1997*, 6. International Waste Management and Landfill Symposium, CISA, Cagliari, Vol. III, pp. 101 – 113

Leong, E.-C., Tripathy, S., Rahardjo, H. 2003. Total suction measurement of unsaturated soils with a device using chilled-mirror dew-point technique. *Géotechnique*, Vol. 53, No. 2, pp. 173 – 182

Lu, N., Likos, W. J. 2004. *Unsaturated Soil Mechanics*. John Wiley & Sons, Inc., New Jersey

Meißner, H., Wendling, S. 1998. Crack formation due to desiccation of mineral liners of landfills. in SECO E PINTO (ed.): *Environmental Geotechnics*, Balkema, Rotterdam, pp. 145 – 150

Mitchell, J. K. 1993. *Fundamental of soil behaviour*. 2nd edition. John Wiley & Sons, NY

Molenkamp, F., Nazemi, A. H. 2003. Interactions between two rough spheres, water bridge and water vapour. *Géotechnique,* Vol. 53, No. 2, pp. 255 – 264

Morris, P. H., Graham, J., Williams, D. J. 1992. Cracking in drying soils. *Can. Geotech.. J.,* Vol. 29, pp. 263 – 277

Nagaraj, T. S., Miura, N. 2001. *Soft clay behaviour – analysis and assessment*. Balkema, Rotterdam

Schubert, H. 1982. *Kapillarität in porösen Feststoffsystemen*. Springer Verlag, Heidelberg

Schubert, H., Herrmann, W., Rumpf, H. 1975. Deformation Behaviour of Agglomerates under Tensile Stress. *Powder Technology*, Vol. 11, pp. 121 – 131

Snyder, V. A., Miller, R. D. 1985. Tensile strength of unsaturated soils. *Soil Sci. Soc. Am. J.*, Vol. 49, pp. 58 – 65

Tang, G. X., Graham, J. 2000. A method for testing tensile strength in unsaturated soils, *Geotechnical Testing Journal*, Vol. 23, No. 3, pp. 377 – 382