Tensile Strength of Consolidated Clay Using Indirect Tests Under Desiccation and Mechanical Loading

B.M. Shannon[1], and J.K. Kodikara[2]

[1]Department of Civil Engineering, Monash University, Clayton; PH (043) 354-2239; email: benjamin.shannon@monash.edu
[2]Department of Civil Engineering, Monash University, Clayton; PH (039) 905-4944; email: jayantha.kodikara@monash.edu

ABSTRACT

Tensile cracking of soils is of great importance in many applications including earth dam engineering, design of clay liners for waste contaminant systems, and agricultural engineering. The behaviour of cracked clay can vary dramatically compared to intact clay influencing key parameters such as permeability or causing preferential flow paths. This paper presents analytical test results of clay soil cracking under desiccation restrained shrinkage and load induced cracking. A new test method has been devised at Monash University to study and measure the shrinkage cracking potential of shrinking soils. The restrained desiccation experiment consists of an inner steel cylinder which restrains the outer consolidated soil ring as it shrinks. Results of tensile strength and strain are compared with load induced cracking from Indirect Diametrical Tests (IDT) on consolidated desiccated soil. Tensile strength was found to be higher in IDT tests as shear and tensile strength were both influencing the results.

Keywords: Restrained shrinkage, IDT, consolidated clay, tensile, cracking

1 INTRODUCTION

Tensile strength of unsaturated soils is an important parameter but not very well defined. The need for a simple yet effective procedure to determine tensile strength from load and desiccation induced cracking is important. Cracking of clay soils is common in many engineering applications including clay liners for waste disposal where the liner moves due to the settlement of waste or undergo desiccation, slopes where loading or influent of water at the top may form a tension crack, and agricultural engineering and environmental remediation.

Cracking can occur primarily due to build up of stress within the soil medium due to loading, desiccation or other means (chemical). Soil tensile strength has been studied previously using both direct and indirect methods. The direct method involves applications of a tensile force directly to the specimen until failure occurs (Nahlawi, et al., 2004, Wang, et al., 2007, Zeh & Witt, 2007, Lakshmikantha, 2009). Indirect methods involve measuring tensile strength indirectly often through compression in tests such as splitting cylinder or Indirect diametrical tension (IDT) tests (Narain & Rawat, 1970, Guérif, 1990, Munkholm & Kay, 2002), beam tests (Ajaz & Parry, 1975, Thusyanthan, et al., 2007) or hollow cylinder tests (Ayad, et al., 1997). Desiccation induced cracking has been studied since the 1900s, however the majority of the work deals with crack pattern analysis or qualitative crack data (Corte & Higashi, 1960, Costa, 2009). Less work has focussed on measuring the build up of tensile stress in a desiccating soil.

This paper presents results of two indirect tensile tests on consolidated kaolin clay specimens under load and desiccation induced cracking. Data are obtained for a large range of water contents for the IDT test and the data results are compared with the restrained ring test. Discussions on discrepancies between the two results are also given.

2 TENSILE TESTS USED

2.1 Indirect Diametrical Tensile test

The Indirect diametrical (IDT) test, commonly known as the Brazilian test (as it was original developed in Brazil) or splitting cylinder, uses an indirect method to determine tensile strength. Originally used for the measurement of tensile strength of rocks, cylindrical samples are subjected to a compressive load in a vertical direction until the sample fails. It is assumed that the samples follow the theory of elasticity where the centre experiences the highest lateral tensile stress caused by the compressive stresses at the top and base of the specimen. The test has been used widely in soil tensile strength since the method is easy to follow and disturbed or undisturbed soil samples can easily be made use of.

Equation (1) is used to calculate the tensile strength of a failed specimen,

(1)

Where: σ_t is the tensile strength, F is the force required to fracture the specimen, d is the diameter of the specimen and t is the height (or thickness) of the specimen.

Vesga and Vallejo (2006) used the Brazilian test on kaolin clay specimens with varying moisture contents. The results showed that the tensile strength was similar to that of a direct method when the results were corrected for the area that was in pure tension. Guérif (1990) used the Brazilian test for a large sample of soils with varying clay contents. The overall tensile strength and the aggregate tensile strength were compared. It was found that the higher the initial water content the higher tensile strength after drying, and that the tensile strength increased with increasing clay content.

The work of Ibarra et al. (2005) combined variable moisture content and bulk density of St Benoit sandy loam. The results found for desiccating soil properties show an increase in tensile strength for all tests following an exponential curve with decrease in water content. As their samples contained a large proportion of sand (>80%) tensile strength may remain high for low moisture contents.

2.2 Restrained ring test

The restrained ring tests consist of a (compacted, consolidated or liquid state) soil annulus in which a rigid ring is placed into the centre of the sample. As the soil looses moisture and shrinks, the rigid ring confines this movement which results in a build up of compressive radial stress in the soil. Tensile stresses develop in the hoop (circumferential) direction where the stress increases the closer to the restraining ring. This tensile stress causes the soil specimen to crack from the interface between the outside of the steel ring and soil. The crack will propagate until the restraining stresses are too small for further propagation or the soil crack has reached the end of the soil sample.

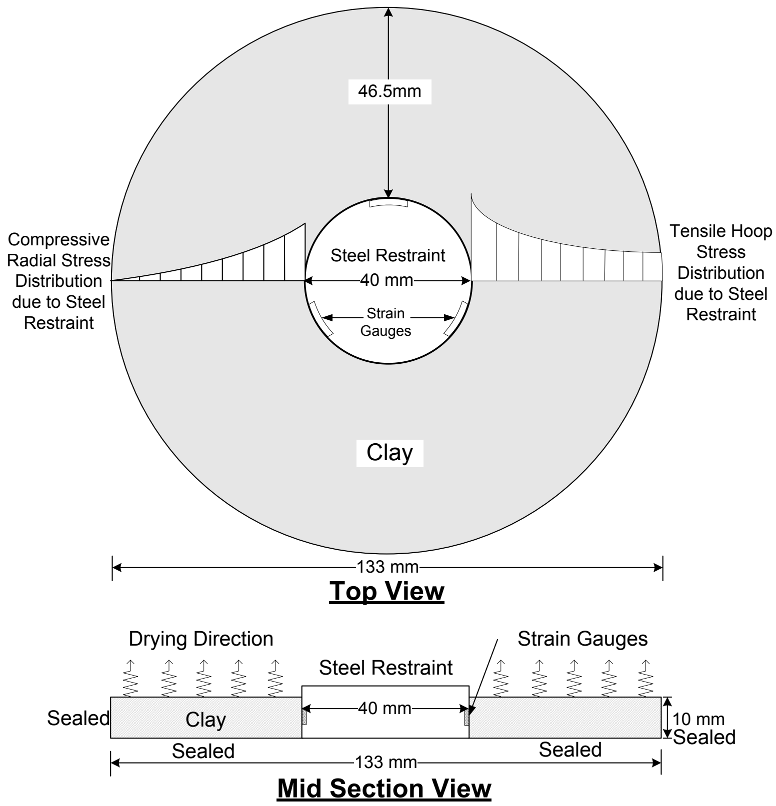


Figure 1. Restrained ring experiment dimensions and *stress distribution*

The restrained ring test has been used for several decades using concrete samples (Bennett & Loat, 1970, 1988); it has only been used recently for soil testing (Abou Najm, et al., 2009, Costa, 2009, Shannon, et al., 2011). The basic principal is derived from early literature on stress distribution in a hollow cylinder (Timoshenko & Goodier, 1951). Equation 2 was used to determine the tensile hoop stress of the sample.

—— —— (2)

Where σ_θ is the tensile hoop stress, r_1 is the interface radius of the steel ring and clay, r_2 is the radius of the outer clay, E_R is the Young's Modulus of the steel circular ring, ε_R is the strain in the ring measured by the strain gauges. E_R was determined by calibrating the ring using static compaction of sand around the strain gauged ring and calculating the passive pressure on the ring.

3 METHODS

3.1 Preparing the consolidated dried soil specimens

For both tests Kaolin NY clay powder (Table 1) was mixed vigorously into a slurry state with a gravimetric water content close to twice the liquid limit (100%) and left for at least 24 hours to homogenize. A known weight of slurry was placed in a consolidation chamber to consolidate the sample to a vertical effective stress of 100 – 200 kPa. A high initial moisture content and careful placement ensured the sample remained saturated. Load was placed in gradual steps and left until at least 90% consolidation had taken place. Load was applied in a stepwise manner up to a final vertical effective stress of 100 – 200 kPa (100 kPa for restrained ring tests). The air entry value of kaolin is considered to be about 110 kPa (Thusyanthan et al. 2007). Unloading was carried out in stages less than 100 kPa while the sample had access to free water so that at any stage suction did not exceed the air entry value. However once the vertical effective stress was reduced to 25 kPa the remaining water was removed from the sample, and the sample was allowed to unload to create an initial suction of 25 kPa, but remained capillary saturated. The soil blocks/cylinders were then extracted from the consolidation chamber to prepare for testing.

Table 1: Kaolin properties used in testing

	Kaolin Prestige NY
Initial Gravimetric Water Content (%)	100 ≈ 2×LL
Liquid limit, LL (%)	54.8
Plastic Limit, PL (%)	26.0
Plasticity Index, PI	28.8
Specific Gravity, G_s	2.62
Linear Shrinkage (%)	6.90
Passing number 75 µm sieve (%)	99.9
Finer than 0.002 mm (clay fraction) (%)	70.8
USCS soil Group	CH
Average Compression Index, c_c (λ)	0.40 (0.173)
Average Swelling index, c_s (κ)	0.11 (0.046)

For the IDT test, individual samples were cut from specialised cutting rings with a diameter of 76 mm and a height of 26 mm. The ring was pushed through the soft soil sample and the sample was trimmed to the correct height. Samples were removed from the ring and the weight of each sample after cutting was recorded. Samples were left to desiccate in a controlled room temperature environment of 21°C from a starting water content of 43.2% (Figure 2). The weight was recorded every hour and samples were rotated until the target moisture content was reached. At the end of each stage samples were wrapped in polythene and aluminium foil and placed in an airtight container for 24 hours to homogenise. IDT tests were conducted for 12 different gravimetric water contents which ranged from 4 to 42%

Figure 2. Cylindrical kaolin IDT samples during controlled desiccation

3.2 IDT and restrained ring testing arrangement

An indirect diametrical tensile test was used from a modified triaxial setup (Figure 3 left). Testing was conducted on clay cylinders using a mechanical test frame. The test frame was created using a Wykeham Farrance stepless compression test machine loading frame where the cross head movement was from the base of the machine. An LVDT was used to measure the cross head displacement and a load cell measured the force transmitted through the sample. Data were recorded using a Datataker in 1 second increments and the cross-head displacement speed was set to 1 mm/min. Tests were loaded until failure of the specimen. Cylinder displacement varied from around 1 – 14 mm before failure depending on water content.

For the restrained shrinkage test after removing a circular sample from the consolidation cell, a circular hole was cut in the middle using a thin wall stainless steel ring 40 mm diameter. The sample was placed on a Perspex plate coated with petroleum jelly and hydraulic oil to reduce the shrinkage friction with a hollow steel cylinder or ring fixed in the middle. The outer perimeter of the soil was coated in petroleum jelly to allow for moisture loss only from the top surface. The sample was left to dry under controlled room temperature (22°C 2°C) from an average starting moisture content of 48.5%. The setup was placed on a balance to record the weight loss at 1 minute intervals throughout the test. Three strain gauges recorded the strain in the steel ring through a datataker at one minute intervals (Figure 3 right). Images were taken with an 8 Megapixel canon camera at 5 minute intervals to determine when cracking initiated. Two restrained ring tests were conducted.

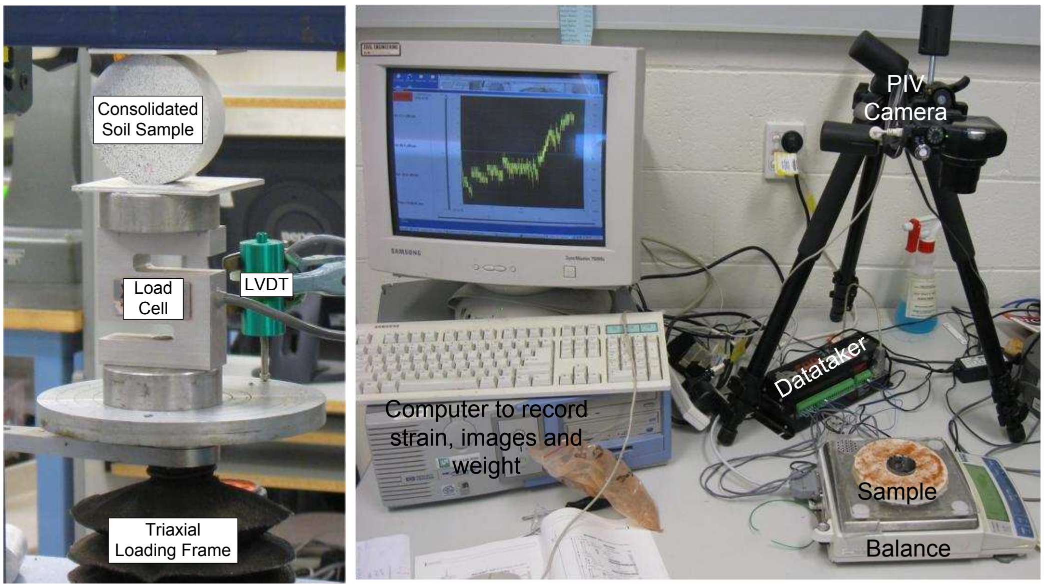


Figure 3. IDT loading arrangement for IDT cylindrical kaolin samples and restrained shrinkage tests (left) and testing arrangement for the restrained ring test (right)

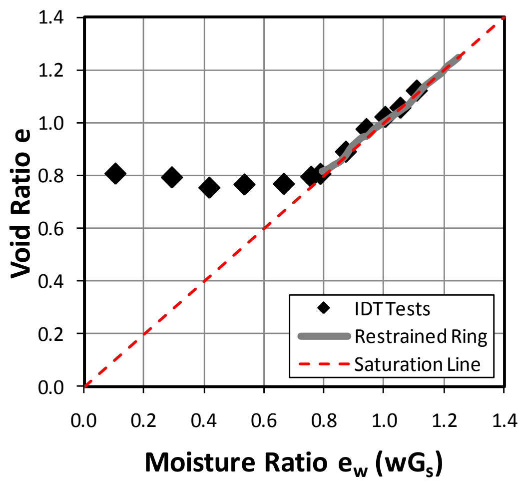
4 RESULTS

Results show that under lab desiccation conditions both soil remained close to saturation until a moisture ratio of 0.8 (water content of 30.5%). Figure 4a shows the void ratio (e) calculated from the volume vs. the moisture ratio (wG_s) calculated from the water content (w) multiplied by the specific gravity (G_s). As the gradient of the lines follows the saturation line it is considered that the sample remains close to saturation (Saturation >96%). Once the sample passes a void ratio of 0.8 it begins to deviate from the saturation line indicating the volume loss is not all water and hence air is entering the sample.

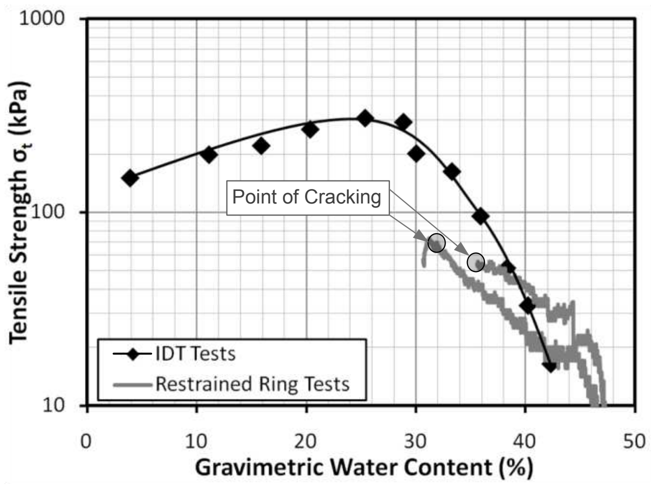
The IDT results (grey diamonds) in Figure 4b show tensile strength vs. gravimetric water content. When samples are desiccated then loaded using IDT, peak strength increases up until a certain moisture content and decreases again after this point. The results are similar to Vesga and Vallego (2005) where the authors pointed out saturation zones. The peak tensile strength (300 kPa) for kaolin NY clay under IDT testing occurred at a water content of 25% (e_w=0.66) indicating the sample is in a complete pendular state (unsaturated). Tensile strength declined after this water content (when in the residual and zero shrinkage phase). The trend of the specimens were such that at higher moisture contents the failure trends showed a ductile behaviour and as the moisture content reduced the samples failed in a brittle manner.

The grey lines in Figure 4b show the strain gauge result readings converted into tensile stress from the restrained ring test. The dot point corresponds to the point of cracking hence the tensile strength of that test. Of two restrained ring tests conducted the cracking water content was 31.3% and 35.6% and the tensile strength at cracking was 70 kPa and 55 kPa respectively. As previously stated these tests started at a higher moisture content than that of the IDT tests due to the lower consolidation pressure.

The tensile strengths determined from desiccation tests are somewhat lower than that determined from the results of the IDT tests, which predicts a tensile strength of 170 kPa (at w=31.3%) and 95 kPa (at 35.6%) respectively. This could be due to a few reasons including thickness of samples tested, deformation in testing and initial soil preparation. The ring test thickness was 10 mm compared to 26 mm for the IDT test. Samples in the IDT test were observed at higher moisture contents (>25%) to have a high plastic deformation at the ends of the sample. No corrections were made for plastic deformations at the end of sample cylinders. The samples with a higher water content had a tendency to compress more before failure, therefore tensile strength at this range may be over predicted. The soil in the restrained ring test was observed to crack perpendicular from the centre of the steel ring and propagate to the outer edge of the soil. At higher water contents the IDT tests cracked in a shear pattern suggesting that at a high water content the IDT may induce higher tensile stress caused by a combination of shear and tensile stresses than compared to that of the ring test. Differences in initial consolidation pressure could also factor into the higher results readings from the IDT tests. The desiccating samples started from a water content of 42.3% whereas the restrained ring test started from an average water content of around 48%.



(a)



(b)

Figure 4. (a) Void Ratio vs. Moisture Ratio. (b) Tensile stress (σ_t) vs gravimetric water content (%) and Comparisons between Restrained ring test and IDT tests.

Vesga and Vallejo (2006) found that comparisons from IDT test and direct pull apart tests showed that the pull apart method gave an increased tensile strength value. This is not the case in comparison with indirect restrained ring desiccation tests with IDT tests. In future, further researching of the ring test calibration and comparison between desiccation induced cracking and load induced cracking will be examined.

5 CONCLUSION

Tensile strength and cracking behaviour understanding is of importance for clay liners for dam embankments, waste disposal and agricultural applications. Two indirect tests were compared for a kaolin soil: The Indirect Diametrical Tensile (IDT) test and restrained ring desiccation test. The tests examined tensile strength behaviour of consolidated soil samples. Samples in both tests were desiccated at constant room temperature. Samples were close to saturation state until a water content of 30%.

For the load induced cracking IDT tests the tensile strength increased up to a water content of 25% and then decreased. In comparison to the restrained ring test the IDT test results showed a much higher tensile strength. Further research is needed to determine the difference in tensile strength results between the IDT and restrained ring test. It is intended that ring test could be developed as test method for determining cracking potential of clay soils, particularly during desiccation.

6 ACKNOWLEDGEMENTS

The authors would like to thank Ms. Sharlina Morseth for her contributing testing work.

REFERENCES

Abou Najm, M., Mohtar, R. H., Weiss, J. & Braudeau, E. (2009). "Assessing internal stress evolution in unsaturated soils". Water Resources Research, 45(W00C11): 1-18.

Ajaz, A. & Parry, R. G. H. (1975). "Stress-strain behaviour of two compacted clays in tension and compression". Géotechnique, 25(3): 495-512.

Ayad, R., Konrad, J.-M. & Soulié, M. (1997). "Desiccation of a sensitive clay: Application of the model crack". Can. Geotech. J., 34: 943-951.

Bennett, E. W. & Loat, D. R. (1970). "Shrinkage and creep of concrete as affected by the fineness of portland cement". Magazine of Concrete Research, 22(71): 69-78.

Carlson, R. W. & Readin, T. J. (1988). "Model study of shrinkage cracking in concrete building walls". ACI Strctural Journal, 85(4): 395-404.

Corte, A. E. & Higashi, A. 1960. Experimental research on desiccation cracks in soil. Research Report, Report, U.S. Army Snow Ice and Permafrost Research Establishment, Illinois, USA.

Costa, S. 2009. *Study of desiccation cracking and fracture properties of clay soils*. PHD Thesis, Monash University, Clayton.

Guérif, J. (1990). "Factors influencing compaction-induced increases in soil strength". Soil and Tillage Research, 16(1-2): 167-178.

Ibarra, S. Y., McKyes, E. & Broughton, R. S. (2005). "Measurement of tensile strength of unsaturated sandy loam soil". Soil and Tillage Research, 81(1): 15-23.

Lakshmikantha, M. R. 2009. *Experimental and theoretical analysis of cracking in drying soils*. Universitat Politècnica de Catalunya, Barcelona.

Munkholm, L. J. & Kay, B. D. (2002). "Effect of water regime on aggregate-tensile strength, rupture energy, and friability". Soil Sci. Soc. Am. J., 66(3): 702-709.

Nahlawi, H., Chakrabarti, S. & Kodikara, J. (2004). "A direct tensile strength testing method for unsaturated geomaterials". Geotechnical Testing Journal, 27(4): 1-6.

Narain, J. & Rawat, P. C. (1970). "Tensile strength of compacted soils". Journal of Soil Mechanics and Foundations, 96(6): 2185-2190.

Shannon, B. M., Rajeev, P. & Kodikara, J. K. (2011). "Numerical modeling of restrained clay desiccation shrinkage using *flac*^{3d}". In 2nd International FLAC/DEM Symposium. Edited by Sainsbury, D., Hart, R., Detournay, C. & Nelson, M. Melbourne, Australia. Itasca, pp. 407-414.

Thusyanthan, N. I., Take, W. A., Madabhushi, S. P. G. & Bolton, M. D. (2007). "Crack initiation in clay observed in beam bending". Géotechnique, 57(6): 581-594.

Timoshenko, S. & Goodier, J. N. (1951). "Theory of elasticity". McGraw-Hill Book Company, Inc., Pennsylvania.

Vesga, L. F. & Vallejo, L. E. (2006). "Direct and indirect tensile tests for measuring the equivalent effective stress in a kaolinite clay". *In.* ASCE, Carefree, Arizona, USA, pp. 106-106.

Wang, J.-J., Zhu, J.-G., Chiu, C. F. & Zhang, H. (2007). "Experimental study on fracture toughness and tensile strength of a clay". Engineering Geology, 94(1-2): 65-75.

Zeh, R. M. & Witt, K. J. (2007). "The tensile strength of compacted clays as affected by suction and soil structure". Experimental Unsaturated Soil Mechanics, 112(3): 219-226.