Measuring total suctions by psychrometers in triaxial tests

Mesure des succions totales en utilisant des psychromètres lors d'essais triaxiaux

X.Tang & J.Graham – *The University of Manitoba, Winnipeg, Man., Canada*
A.W.-L.Wan – *AECL Whiteshell Laboratories, Pinawa, Man., Canada*

ABSTRACT: To examine suction in unsaturated soils, the conventional triaxial apparatus must be modified so that suctions can be controlled or measured. This paper describes two techniques for using psychrometers to measure suctions in triaxial specimens of a highly-plastic compacted sand-bentonite. Suctions ranged from about 2 MPa to 8 MPa for degrees of saturation from 98% down to 65%. They decreased when specimens were subjected to increasing confining pressures, but appeared to be independent of the shear component of the stress tensor. The proposed techniques for using psychrometers provide a reliable approach for monitoring suction changes during loading.

RESUME: Pour examiner la succion dans des sols non saturés, les appareils triaxiaux doivent être modifiés afin que la succion puisse être contrôlée ou mesurée. Cet article décrit deux techniques qui incorporent les psychromètres pour le mesurage des succions dans des spécimènes triaxiaux d'un mélange sable-bentonite à plasticité élevée. Les succions ont variés d'environ 2 MPa à 8 MPa avec des degrès de saturation variant de 98% à 65%. Les succions ont decru quand des spécimens ont été soumis à la croissance de pression de confinement, mais semblent être indépendentes du component de cisaillement de la contrainte tenseur. Les psychromètres fournissent une approche fiable pour le monitorage des changements de succion.

1 INTRODUCTION

New constitutive models and conceptual frameworks have recently been proposed for rationalizing the behavior of unsaturated soils (for example, Gens and Alonso 1992, Wheeler and Sivakumar 1995, Delage and Graham 1995). To quantify these models, suctions must be controlled or measured during testing. In unsaturated sands, silts, and low-plastic clays, suctions are dominated by capillary effects and are relatively low. For these soils, oedometers and triaxial cells can be readily modified so that pore air pressure and pore water pressure can be separately controlled or measured using the axis translation technique (Fredlund and Rahardjo 1993). In highly plastic clays however, suctions are influenced strongly by physico-chemical effects (Gens and Alonso 1992), and their suctions are much higher. Axis translation can no longer be used because porous disks with sufficiently high air entry value are not available. Alternative techniques must be sought. Psychrometers are commonly used in soil physics for measuring total suctions up to about 8 MPa. Experience is developing in geotechnical testing under both laboratory and field conditions (for example Wan 1996, Graham 1996a,b).

Thermocouple psychrometers estimate total suction or free energy of soil water in unsaturated soils by evaluating relative humidity in the air phase (Fredlund and Rahardjo 1993). To enable suctions to be measured in the stress fields of triaxial tests, psychrometers must be carefully selected and installed so that they can withstand damage and offer minimum disturbance to specimens. One approach inserts a psychrometer inside a plastic load cap in contact with the specimen (Edil and Motan 1984). This may lead to damage and contamination of the thermocouple because its protective shield is removed. This approach can be improved by placing the psychrometer into a small hole drilled in the top of the specimen (Graham *et al.* 1996a). A second approach embeds a psychrometer in the center of a specimen during compaction (Wan 1996). This makes compaction more complicated and may lead to specimen disturbance that affects the mechanical behaviour. This paper compares results from both approaches. It shows that psychrometers provide reliable and effective means of incorporating suction measurement into triaxial testing.

2 TESTING FACILITIES

2.1 *Techniques for installing psychrometers in triaxial testing*

Two types of Wescor psychrometers were used in this study. They operated using the same principles, but differed in the porous shields protecting the thermocouples. Some of the shields were porous ceramic 7 mm diameter, 10 mm long. The remainder were stainless steel with smaller size, 5 mm diameter, 7 mm long. They provided faster response and additional strength to withstand stresses in triaxial testing. The psychrometers were controlled using a Wescor HR-33T, Wescor PR-55, or a Campbell Scientific CR-7 measurement and control system. The HR-33T system is operated manually while the CR-7 system controls and supplies cooling current automatically to the psychrometers. A major advantage of the CR-7 is that it tracks and records the output history of the psychrometers during the course of measurements. The manual and automatic instruments appear to produce accurate and reliable results.

2.2 *Triaxial test apparatus*

Three triaxial cells at the University of Manitoba can operate under pressures up to 10 MPa and temperatures up to 100°C (Fig.1). The cells use internal tie-rods that allow mounting and inspection of all instrumentation before the cell sleeve is positioned and the cell fluid added. The thermal stability and low electrical conductivity of silicone oil used as the cell fluid allows the load cell and lateral displacement transducers to be used inside the cell. The tests described here were performed at room temperature and pressures up to 3.5 MPa. Other work has examined psychrometer performance at higher temperatures.

Figure 1 also shows two arrangements for embedding psychrometers in triaxial specimens. In type (a), the psychrometer (PST) is mounted in the loading cap with its stainless-steel shield protruding into a small hole drilled into the top of the specimen (Graham *et al.* 1996a). In this installation, the psychrometer readings may be affected by end effects, but produces little disturbance in the specimen. In type (b), a ceramic-tip psychrometer (PCT) is embedded at specimen mid-height (Wan 1996). This means that it is remote from end disturbance. However, because of its size and its connecting cable, it may affect stress-strain behaviour in the triaxially stressed zone in the middle of the specimen. Psychrometers installed in both ways can sense relative humidity (and hence suction) in the air phase of specimens during compression and shear (Wan 1996, Graham *et al.* 1996a).

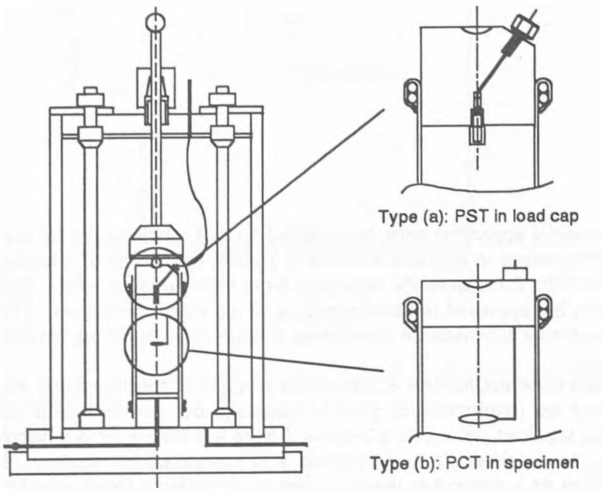

Figure 1. Triaxial cell and psychrometer installation types (a) and (b)

3 CALIBRATION OF PSYCHROMETERS

A thermocouple psychrometer consists of a sensing junction and a reference junction protected by a shield. It makes use of cooling produced by the Peltier effect to condense a small amount of moisture inside the shield on to the sensing junction. As the condensed water evaporates, a potential difference is set up between the sensing junction and the reference junctions. This creates an induced electric current in the thermocouple loop due to the Seebeck effect. The magnitude of the current depends primarily on the rate of evaporation of the condensed water. In turn, this depends on the suction and the temperature in the soil (Brown 1970).

Procedures for psychrometer calibration have been well described in the open literature (Meyn and White 1972, Fredlund and Rahardjo 1993). The ceramic psychrometers were calibrated by suspending the instruments above KCl solutions with molal concentrations ranging from 0.4 m to 1.0 m, at temperatures from 10°C to 50°C. The stainless steel psychrometers were calibrated by suspending the instruments over NaCl solutions with concentrations of 0.5 m, 1.0 m and 1.5 m. These calibrations were performed in a temperature controlled room at 25.7±0.05°C.

Figure 2 shows results from the CR-7 for relationships between corrected microvolt output and known suctions. The best fit equation for each calibration exhibits good linearity, though each calibration line has an intercept value which is not negligible. Psychrometers operated by the CR-7 should be calibrated using a 2-parameter linear equation (slope plus intercept). The conventional approach of fitting a straight line through the data points and a zero origin may lead to less precise suction values.

Output readings of psychrometers at temperatures other than 25°C were corrected to 25°C by

$$\text{Corrected reading} = \frac{\text{reading}}{0.325 + 0.027 \times T} \qquad (1)$$

where T is temperature in degrees Celsius (Brown 1970, Wan

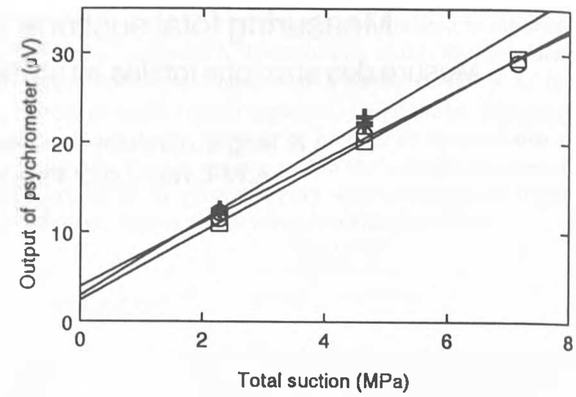

Figure 2. Calibration lines for psychrometers

1996). Figure 3 shows results from a psychrometer in which the temperature varied from about 21.5°C to about 23°C. The output from the psychrometer varied with temperature change. After applying (1), the corrected output and the interpreted suctions were almost constant.

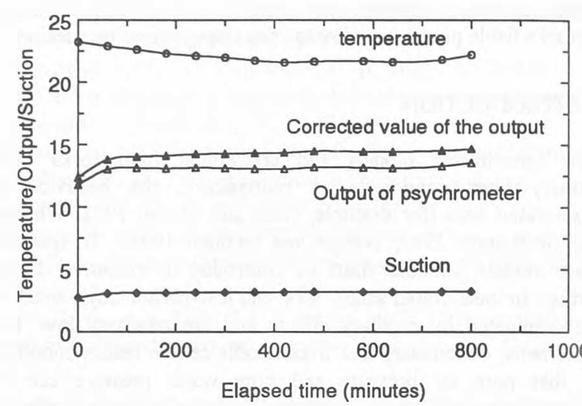

Figure 3. Variation of temperature and suction with time

4 MATERIALS AND SPECIMEN PREPARATION

Specimens were prepared from a sand-bentonite mixture known as 'buffer' that has been proposed for use in the Canadian Nuclear Waste Management Program. The sand is a crushed, medium, sub-angular, well-graded, silica sand. The clay is a sodium-rich bentonite with liquid limit w_L = 230% - 250%, and plasticity index I_p = 200 (Dixon and Gray 1985). The mixture was formed by combining equal dry masses of silica sand and sodium bentonite with water to achieve the desired water content. Type (a) and type (b) specimens had diameters 50 mm and 100 mm respectively; and lengths 100 mm and 200 mm. They were statically compacted to dry densities of 1.41 Mg/m^3 or 1.67 Mg/m^3, but different (controlled) saturations.

5 TEST PROCEDURES

Three different types of triaxial tests were performed. Loading conditions can be categorized as (1) isotropic compression, (2) shearing with constant confining pressure, and (3) shearing at constant mean stress. Test procedures involved the application of required loadings and observation of the establishment of suction equlibrium. No drainage was permitted in either the air or water phases. Hence all tests can be characterized as 'constant mass tests'. The tests were conducted at ambient temperatures from approximately 22°C to 26°C. Psychrometer readings were corrected to the values at 25°C using (1).

5.1 *Equilibrium of initial suctions*

Specimens were encased in two latex rubber membranes which kept moisture contents constant. It will be shown later that water vapor pressures (and hence suctions) in the pore voids varied with confining pressure. When initial set-up was complete, specimens were left for some time to allow potentials to equilibrate under atmospheric pressure in the cell fluid (see Fig.4 before the addition of confining pressure). The stainless steel shields in type (a) installations conservatively took about 2 - 4 hours for equilibration. The ceramic shield instruments in installation type (b) took longer, usually 8 - 10 hours. Typically one day or longer was then allowed before the next phase of testing.

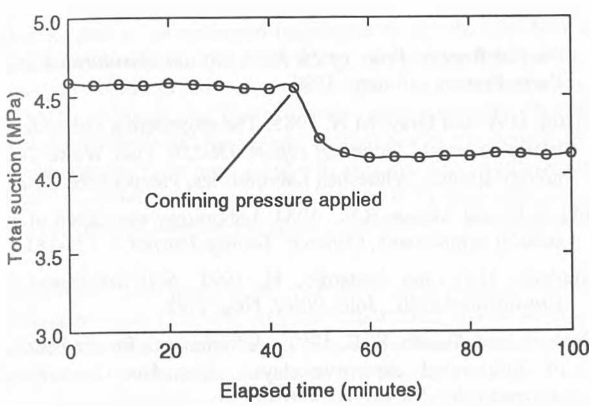

Figure 4. Total suction change under confining pressure of 200 kPa

Figure 5 shows that psychrometers can give reliable long-term readings of suction. Two type (b) specimens were wrapped in plastic sheets and sealed in an air-tight container to prevent moisture loss for about 500 days. Daily readings showed that suctions measured by ceramic psychrometers were virtually constant with time. These findings allowed the psychrometers to be used in a 900-day in-ground experiment at AECL's Underground Research Laboratory (Graham *et al.* 1996b).

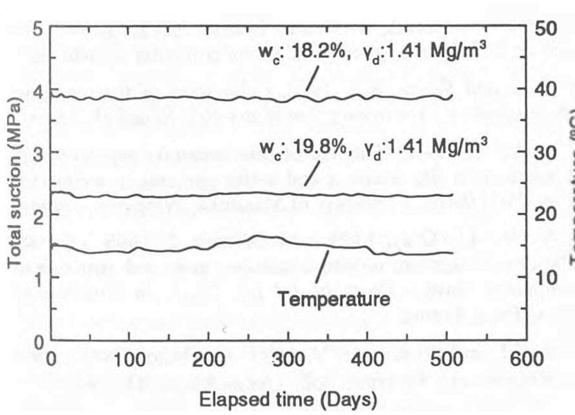

Figure 5. Long term drift of psychrometer output

5.2 *Application of loadings for triaxial tests*

5.2.1 *Isotropic compression* Once the psychrometer reached steady-state values, isotropic loads were applied by increasing the increments of cell pressure and the resulting changes in suction measured by psychrometer. The duration of each pressure increment depended on the deformation of the specimen and time taken to reach constant readings on the psychrometer. Readings using the stainless steel psychrometers in type (a) installations typically took of the order 10 - 20 minutes to reach a steady output (Fig.4). The type (b) installation was again slower.

5.2.2 *Shearing* Stress-controlled and strain-controlled shear tests were both carried out. Strain-control was used for triaxial compression tests with constant confining pressure. The rate of loading and unloading during shear was chosen so that the psychrometer would measure equilibrium values of suctions. Incremental stress-control was used for shearing ($q = \sigma_1 - \sigma_3$ increasing) at constant mean pressure $p = (\sigma_1 + 2\sigma_3)/3$. The durations of load increments were again adjusted to allow equilibrium of deformations and suctions.

6 RESULTS AND INTERPRETATION

6.1 *Isotropic compression*

Figure 6 shows results from tests on two similar specimens of unsaturated buffer that used type (a) and type (b) psychrometer installations. The respective values of water content w = 19.5% and 18.7%; the saturations S_r = 85% and 80%; and the dry densities γ_d = 1.67 Mg/m^3 and 1.66 Mg/m^3. At the beginning of loading, the suctions were 3.9 MPa and 4.4 MPa respectively. Addition of confining pressures up to 3.5 MPa caused significant reductions of suction to approximately 1.5 MPa, probably as a result of compression of the air phase and increasing saturation. Unloading returned the suctions almost to their initial values. That is, the changes in suction were largely recoverable, suggesting the applicability of an elastic-plastic model for unsaturated soils (Delage and Graham 1995).

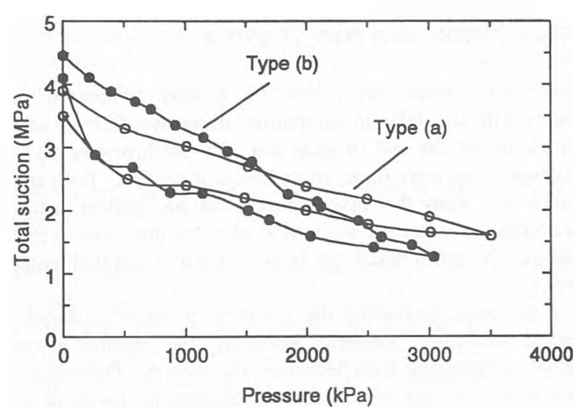

Figure 6. Total suction versus pressure under isotropic compression

6.2 *Triaxial compression with constant confining pressure*

Figure 7 shows how suctions decrease with increasing deviator stress in traditional triaxial compression tests. The initial values for type (a) and type (b) were respectively w = 17.4% and 18.6%; S_r = 75% and 55%; γ_d = 1.67 Mg/m^3 and 1.41 Mg/m^3; confining (cell) pressures = 0.20 MPa and 0.52 MPa; and axial strain rate $\dot{\varepsilon}_1$ = 0.60 %/hr and 0.035 %/hr. Here again, the changes in suction appear to be reversible. Results from a more extensive series of tests were examined by Wan (1996) (Delage and Graham 1995).

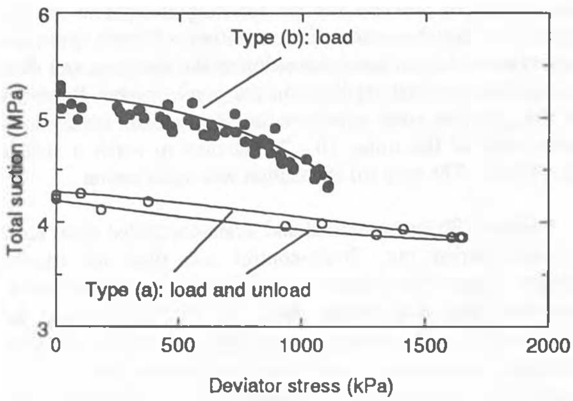

Figure 7. Total suction versus deviator stress under shearing

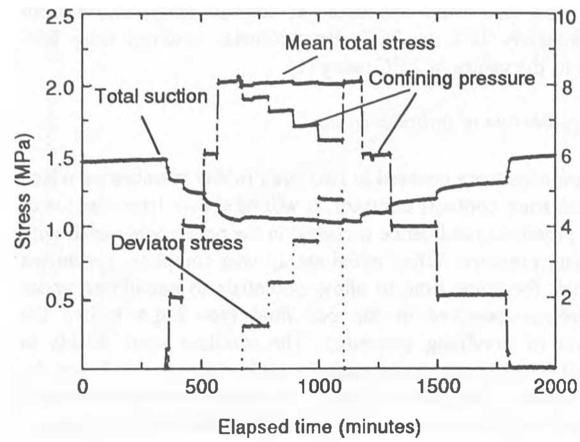

Figure 8. Total suctions in response to deviator stress at constant mean total stress (temperature: 29°C)

6.3 *Triaxial compression with constant mean stress*

The question then arises whether the decreases in suctions shown in Fig.7 result from increasing shear stress, or the accompanying increases in mean stress ($\Delta q/\Delta p = 3$). It is easy to envision ΔS changing with Δp, but less easy to understand it changing with Δq. Figure 8 represents data from a specimen (w = 17.3%, S_r = 75%. γ_d = 1.67 Mg/m^3) that was sheared incrementally using $\Delta\sigma_1 = -0.5\Delta\sigma_3$, so that $\Delta p = 0$. The test was performed in a type (a) installation at 29°C. The mean stress was 2 MPa and the maximum deviator stress 1.2 MPa. Before applying the initial isotropic confining pressure, the suction was 6.0 MPa. Adding 2 MPa confining pressure then caused the suction to reduce to about 4.2 MPa. The following phase involved increasing the deviator stress with the mean stress held constant. During this time the suction remained essentially constant. Unloading the deviator stress and mean stress caused the suction to return to its initial value of 6.0 MPa.

7 DISCUSSION AND CONCLUSIONS

These results come from tests on densely compacted sand-bentonite in two different laboratories using two different test installations. At the end of each test, the psychrometer tips and specimen holes were found to be free of distortion. Both sets of experiments show that psychrometers can be installed in triaxial specimens and can read suctions at elevated pressures over long periods. (A similar result has been obtained at elevated temperatures.)

In all cases, increasing the confining pressure produced decreased suctions. Similarly, increasing the deviator stress in triaxial compression tests decreased the suction. Preliminary results show that this corresponds to changes in the mean stress component of the stress tensor and is independent of the shear stress component. In these specimens, the changes in suction with mean stress were largely reversible.

While type (a) and type (b) installations both produced decreasing suctions, the rates of suction decrease in Figs.6,7 were not the same. It is not clear at present whether this arises from slight differences in specimen preparation or from the different locations of the psychrometers.

REFERENCES

Brown, R.W. 1970. Measurement of water potential with thermocouple psychrometers: construction and application. *USDA For. Serv. Res. Pap. INT-80, Intermt. For. and Range Exp. Stn., Ogden, Utah.*

Delage, P. and Graham, J. 1995. Understanding the behavior of unsaturated soils requires reliable conceptual model. State of the Art Report. *Proc. of 1st Int. Conf. on Unsaturated Soils.* Paris, France. 6-8 Sept. 1995.

Dixon, D.A. and Gray, M.N. 1985. The engineering properties of buffer material. *Technical report TR-350,* Fuel Waste Technology Branch, Whiteshell Laboratories, Pinawa MB, Canada.

Edil, T.B. and Motan, S.E. 1984. Laboratory evaluation of soil suction components, *Geotech. Testing Journal* 7, 173-181.

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

Gens, A. and Alonso, E. E. 1992. A framework for the behavior of unsaturated expansive clays. *Canadian Geotechnical Journal.* Vol. 29. pp. 1013-1032.

Gens, A. and Alonso, E. E. 1992. A framework for the behavior of unsaturated expansive clays. *Canadian Geotechnical Journal.* Vol. 29. pp. 1013-1032.

Graham, J., Wiebe, B., Tang, X. and Onofrei, C. 1995. Strength and stiffness of unsaturated sand-bentonite 'buffer', *Proc. of 1st Int. Conf. on Unsaturated Soils.* Paris, France.

Graham, J., Tang, X., Wiebe, B., Zhou, Y. and Rajapakse, R.K.N.D. 1996a. Modelling of sand-bentonite buffer for use in the Canadian Nuclear Fuel Waste Management Program. *Final Report*: Contact No. WS102679.

Graham, J., with Chandler, N., Dixon, D.A., Roach, P.J., To, T. and Wan, A.W.L. 1996b. The buffer/container experiment: Volume 4 - results, synthesis, issues. AECL pp.344 plus approx. 200 figures, photographs, and computer animations.

Meyn, R.L. and White, R.S. 1972. Calibration of thermocouple psychrometers *Psychrometry in Water Rel. Research.* 56-63.

Wan, A. W. -L. 1996. The use of thermocouple psychrometers to measure in situ suctions and water contents in compacted clays. *PhD thesis,* University of Manitoba, Winnipeg, Canada.

Wan, A. W. -L., Gray, M.N. and Graham, J. 1995. On the relations of suction, moisture content, and soil structure in compacted clays. *Proc. of 1st Int. Conf. on Unsaturated Soils.* Paris, France.

Wheeler, S.J. and Sivakumar, V. 1995. An elasto-plastic critical state framework for unsat. soil. *Geotechnique* 45, 35-53.

ACKNOWLEDGMENTS

This research was funded by the Nat. Sciences and Eng. Res. Council of Canada; and by Atomic Energy of Canada Limited and Ontario Hydro through the Candu Owners Group. N. Piamsalee provided valuable technical support. Discussions with D.A.Dixon, M.N.Gray, B.Wiebe and G.Ferris are gratefully acknowledged.