Behavioral influence of specimen preparation methods for unsaturated plastic compacted clays

Influence des méthodes de préparation d'échantillons sur comportementale des argiles plastiques non-saturées et compactées

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ABSTRACT: The University of Manitoba is conducting research on 'buffer' material as part of an ongoing research effort aimed at developing a reliable concept for deep underground burial of nuclear fuel waste. Buffer material is a compacted mixture comprised of 50% bentonite clay and 50% quartz sand. Extensive laboratory testing has been undertaken to identify the influence of specimen preparation methods on the behavioural characteristics of buffer. Following specimen preparation, specimens were immediately sheared under 'quick' undrained conditions in a triaxial cell. Results of stiffness and strength for specimens prepared using the two methods are presented. The results are compared and reasons presented for the observed differences in behaviour. The conclusions provide insight into the impact of specimen preparation procedure on the behaviour of unsaturated sand-clay mixture.

RÉSUMÉ: L'Université du Manitoba effectue de la recherche sur les tampons au sein d'un programme continu de recherche ayant pour but de développer un concept fiable pour l'enfouissement profond de déchets de carburant radioactif. Le tampon est composé de matériel compacté qui contient de l'argile et du sable de quartz. Des expériences extensives en laboratoire ont été entreprises pour identifier l'influence de la préparation des échantillons sur les caractéristiques comportementales du matériel tampon. Deux méthodes de préparation furent utilisées pour modifier la succion initiale du sol. Suivant la préparation des échantillons, ceux-ci furent immédiatement cisaillés dans un appareil triaxial, sous des conditions non - drainées. Les résultats sont comparés et les différences de comportement sont discutées. Les conclusions fournissent des connaissances sur l'impact des procédures de préparation des échantillons sur le comportement des mélanges de sable et d'argile non - saturées.

1 INTRODUCTION

This paper presents results of an experimental testing program targeted at identifying shear strength of an unsaturated sand clay mixture (commonly referred to as 'buffer') under undrained loading. The experimental program was designed to determine the strength parameters and stress-strain response for a proposed mixture that will be subjected to mechanical loads from compaction equipment, and later, service loading from an environment with widely varying temperatures and water contents. In order to understand the material behaviour under these conditions, the impact of water content and therefore suction needs to be examined. At the beginning of the program, suction in specimens was altered by selecting different water contents at the specimen preparation stage. Later, the vapour equilibrium technique was used to increase specimen suction to selected target values. These two techniques for modifying suction in specimens produced different strength and deformation parameters. Since both techniques have a fundamental physical significance in terms of how they represent field performance of the material, this paper serves to discuss the two methods and contrast the impact that preparation procedure has on behavioral properties of the clay-sand mixture.

In its proposed application in the Canadian nuclear fuel waste disposal program, sand-bentonite will be expected to transmit waste heat to surrounding rock and form an advective barrier to groundwater flow. Because of coupling between heat and moisture, a temperature gradient will cause drying near the container and wetting near the rock. The processes of wetting and drying affect the hydro-mechanical characteristics of the buffer material significantly (Graham *et al.* 1997). Different behaviour can be expected at different water contents. Varying suction that represents soil water potential in the soil generates differences in behaviour caused by varying water contents.

Understanding the behaviour of unsaturated soils requires evaluation of five state variables (Wheeler and Sivakumar 1995, Delage and Graham 1995), namely deviator stress q, net mean stress p, suction S, specific volume V, and water content w or degree of saturation S_r. The relationships between suction and the mechanical behaviour of soils can only be examined if suctions can be measured and/or controlled under varying stress conditions.

For the undrained testing series conducted in this research program it was assumed that suction did not vary significantly during the triaxial shearing phase. As such, initial suction in specimens could be taken as the suction at the start and during all stages of loading. This meant that specimens could be prepared using techniques that would vary initial soil suction (Wiebe *et al.* 1998).

Specimens were prepared at various selected suction levels using two broadly different specimen preparation techniques. This allowed evaluation of the influence of suction on strength and stiffness, and determination of properties that can be used in the numerical modeling of unsaturated soils.

2 MATERIALS AND SPECIMEN PREPARATION

The material studied was a 50:50 mixture of sand and clay. The sand was a crushed, medium, sub-angular, well-graded, silica sand. The clay was a sodium-rich bentonite with liquid limit w_L = 230% - 250%, and plasticity index I_p = 200. The mixture was formed by combining equal dry masses of silica sand and bentonite clay with deionized water to achieve a desired water content and density.

Compacted specimens were formed by hand mixing the sand and bentonite with the amount of deaired water required to achieve a desired water content, degree of saturation and dry density after compaction. Following hand mixing, the blend was cured for a standard curing period and then compacted using a rigid one-dimensional static compaction mold. Specimens were compacted in five equal lifts of 20 mm resulting in a final specimen 100 mm in length and 50 mm in diameter. Procedures described by Yarechewski (1993) for compacting triaxial specimens of sand-bentonite were followed.

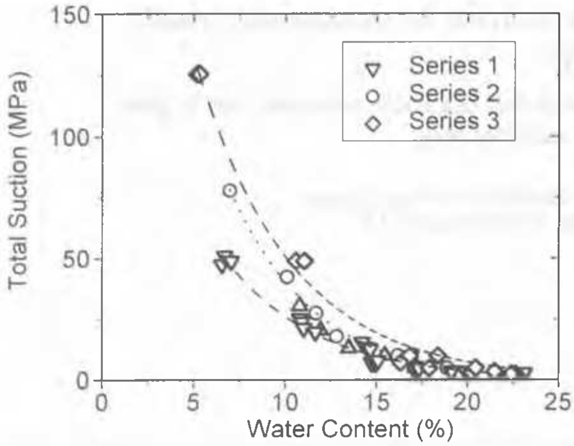

Figure 1. Soil Water Characteristic Curves for Buffer

As mentioned, two different techniques were used to generate suction in compacted triaxial specimens. The suction was varied to examine the strength and stiffness at different combinations of confining pressure and suction. The differences between the two specimen preparation techniques are outlined in the following sections.

2.1 *Series 1 - Specimens Compacted to a Target Suction*

Taking account of the well-known relationship that suction decreases with increasing water content, the suction in the first set of test specimens was modified by varying the water content of the sand-bentonite blend at the mixing stage. Altering the molding water content produced different initial suctions in specimens in the 'as compacted' state at constant dry density.

In order to determine suction at a specific water content, specimens were mixed at various water contents and compacted to the same dry density. Following compaction, specimens were placed in a sealed chamber with Whatman 77 filter papers placed at the top of specimens. Specimens were left to equilibrate for not less than 30 days after which the filter paper was removed and its moisture content measured. Since the two materials were in contact, calibration permitted the suction in the soil specimen to be inferred from the filter paper at the end of equilibration (Tang 1999). The resulting curve of water content *vs.* suction is shown in Figure 1 (Series 1). Multiple specimens were tested at the same initial water contents to examine repeatability of the results. The data show that repeatability of the suction measurement was good over the range of suction examined.

Once the water content - suction curve was developed, it was used to determine the molding water content required for achieving different target suction levels. Approximately thirty specimens were prepared using this approach.

2.2 *Series 2 - Specimens Dried Following Compaction*

Following the first series, a second set of specimens was prepared at various suction levels using an alternative approach to modify the soil suction. In the second series, all specimens were mixed and compacted at Reference Buffer Material (RBM) parameters (w = 19.42%, S_r = 85.0%, and γ_d=1.67 Mg/m3). At this compaction, the total suction was measured to be approximately 3.0 – 4.0 MPa. The compacted specimens were then placed in sealed dessicators in which KCl solutions with known concentrations were used to establish different suction levels. The partial vapour pressure in the headspace above the solution altered the suction in specimens. Specimens were allowed to equilibrate within the sealed environment for not less than thirty days.

Following equilibration, specimens were removed from the sealed containers and their water contents were determined. Knowing suction in the container and water content after equili--bration the soil water characteristic curve could be plotted for the material. This is referred to as the vapour equilibrium technique.

Figure 1 shows the soil water characteristic curve developed using this method (Series 2 and 3) for two different initial saturation's (85% and 98% respectively). It should be noted that the series of specimens at 98% saturation are only used to show the influence of initial molding water content on the shape of the soil water characteristic curve for almost saturated specimens subjected to increased suction following specimen compaction.

2.3 *Comparison of Water Content - Suction Relationships.*

It is important to recognize that the water content - suction relationship is not unique for this compacted material. The curve depends on the initial molding water content and the drying / wetting history of a specimen (Tang *et al.* 1998). As previously mentioned, Figure 1 illustrates water content - suction curves for buffer material prepared in three different ways. The curve for Series 1 is from specimens compacted at different molding water contents (Wiebe 1996). No drying was permitted following compaction of the specimens. The curve for Series 2 shows a Soil Water Characteristic Curve (SWCC) for material compacted to RBM parameters (S_r = 85%) and then subsequently subjected to suction increase as described in section 1.2 (Blatz 2000). The points on the curves represent measurements of water content corresponding to different controlled suction levels. The final curve (Series 3) shows the SWCC for material compacted at an almost "saturated" condition (S_r = 98%) with a molding water content of 22% and subsequently dried to higher suction levels (Tang 1999).

For the last two SWCC's (Series 2 and 3) where specimens were compacted at a consistent target water content and then subsequently dried to various suction levels, the curves are similar in shape, though slightly different in detail. The difference between the two curves indicates that the microstructure of the specimens was affected by the molding water content (Wan *et al.* 1995). The Series 1 specimens in which the suction was modified by altering the initial water contents (Wiebe 1996) represent a further series of different microstructures.

The water content - suction curve for specimens prepared by altering the molding water content shows significantly lower suction than the SWCCs for specimens at the same water content prepared by drying following compaction. The difference in the suction is greatest at lower water contents and therefore higher suctions. The different curves indicate that specimen preparation has a notable impact on the soil structure and hence on suction. It is understood (Wan *et al.* 1995) that specimens compacted at varying water contents do not belong to a single soil water characteristic curve but in fact are points on a series of separate soil water characteristic curves that are unique for each molding water content. This is consistent with the fact that at higher water contents (lower suctions), the curves approach each other. This occurs because the molding water contents of the two series become broadly similar.

By definition, the curve through Wiebe's data (Series 1) does not form a soil water characteristic curve. Each molding water content creates a unique material structure that in turn has its own soil water characteristic curve. As a result, the point for a specific molding water content would in fact represent one point on the soil water characteristic curve for that specific initial condition. Subsequent points on the soil water characteristic curve would be determined by drying / wetting the specimen beyond the initial point. The results in Figure 1 show that the SWCC is not a unique relationship for a specific material but is intimately related to the microstructure. The microstructure in turn is related to the molding water content (Wan *et al.* 1995).

3 TRIAXIAL EQUIPMENT AND PROCEDURES

Quick undrained triaxial tests were used to evaluate the impact of suction, confining pressure and temperature on the strength and stiffness of sand-bentonite buffer. Testing was initiated by Wiebe (1996) who studied the impact of temperature, pressure, and suction on the strength and stiffness of compacted sand-bentonite buffer using Series 1 specimens. Subsequent work by Blatz (2000) (Series 2) extended the testing using a different method of specimen preparation as outlined in section 2. The same load cell, load frame and internal instrumentation were used so that results of the two programs could be easily compared, one exception being that a modern data acquisition system was used in the second program.

3.1 *Quick Undrained (UU) Triaxial Cell and Load Frame*

Figure 2 (a) shows a schematic of the equipment used for the quick undrained tests. Figure 2 (b) is a photograph of the system illustrated in Figure 2 (a). The system included a Brainerd-Kilman (B-K) triaxial cell mounted in a Wykham-Farrance stepless load frame. The B-K cell was used to shear all specimens from cell pressures of 0.2 MPa to 3.0 MPa at ambient room temperature. The B-K cell had two drainage leads from the pedestal to the cell base, both of which incorporated shut-off valves and pressure transducers allowing direct control of air and water drainage. The load cell and axial linear voltage differential transformer (LVDT) were mounted externally.

The system was pressurized using an external tank connected to a nitrogen gas tank supply. Initial testing used silicon oil (Dow Corning 200 Fluid) as the cell fluid. Later in the program, the silicon oil (which had been utilized primarily due to the high temperature tests included in Wiebe's program) was replaced by water. This reduced the time for removal of sheared specimens as the equipment was much easier to handle and clean.

3.2 *Electronic Instrumentation and Data Acquisition System*

Measurements of cell pressure, back pressure, load, and axial displacement were taken using electronic instrumentation and monitored using a PC-based data acquisition system.

The load was measured using an externally mounted load cell with a 500kN capacity attached to the load frame (Figure 2 a). A load ram 12.7 mm in diameter transferred the load from the cell out to the load frame.

Cell pressure and back pressure were monitored using typical microgauge pressure transducers with a maximum capacity of 13.8 MPa. Axial displacement was measured externally using a Hewlett Packard linear voltage differential transformer (LVDT). The LVDT was mounted as shown in Figure 2 (a). All instruments including the load cell, LVDT's, and pressure gauges had a linear R^2 regression coefficient of better than 0.98 for all calibrations. Any instrumentation that did not meet this standard was replaced.

All instruments were powered during calibration and monitoring using a Hewlett Packard 6214B Power Supply with an excitation voltage of 5V. The signals were monitored using a Hewlett Packard 3497A Data Acquisition and Control System. The readings were taken and recorded by a PC-Based data monitoring system using EZDAQ 1.0, a non-commercial software package developed at the University of Manitoba by Dr. Emery Lajtai. The software is capable of graphing the data in real time and can handle both full bridge and half bridge instrumentation.

4 RESULTS OF TRIAXIAL SHEARING

4.1 *Specimen Installation*

Following compaction (specimens from Series 1) and equilibrium in the dessicators (specimens from Series 2) specimens were built into the triaxial apparatus. Lucite discs were placed at top and bottom of the specimens to ensure that no drainage of air or water could occur during any stages of testing. The tests can therefore be identified as 'UU tests'. Two silicone membranes were used for each specimen. Two viton O-rings were placed at the load cap and on the pedestal to seal the specimen from the cell fluid. The cell sleeve was then placed over the specimen and filled with cell fluid. Cell pressure application occurred quickly with no time given for consolidation to occur. Following application of cell pressure shearing was initiated under undrained conditions at a strain rate of 0.2% / min. Specimens were sheared to 16% axial strain to reach large strain conditions. After shearing, specimens were removed from the cell for visual inspection of the failure mode and to measure dimensions and mass. Specimens were cut into five equal lifts and water contents taken. Identical standardized procedures were followed in both programs so that results of this program could be reliably compared with results of the earlier programs (Wiebe 1996).

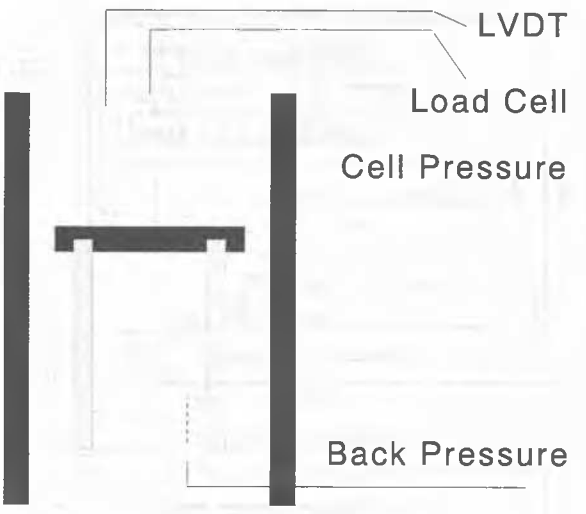

Figure 2 (a) Schematic of the B-K triaxial cell

Figure 2 (b) Photograph of the triaxial system

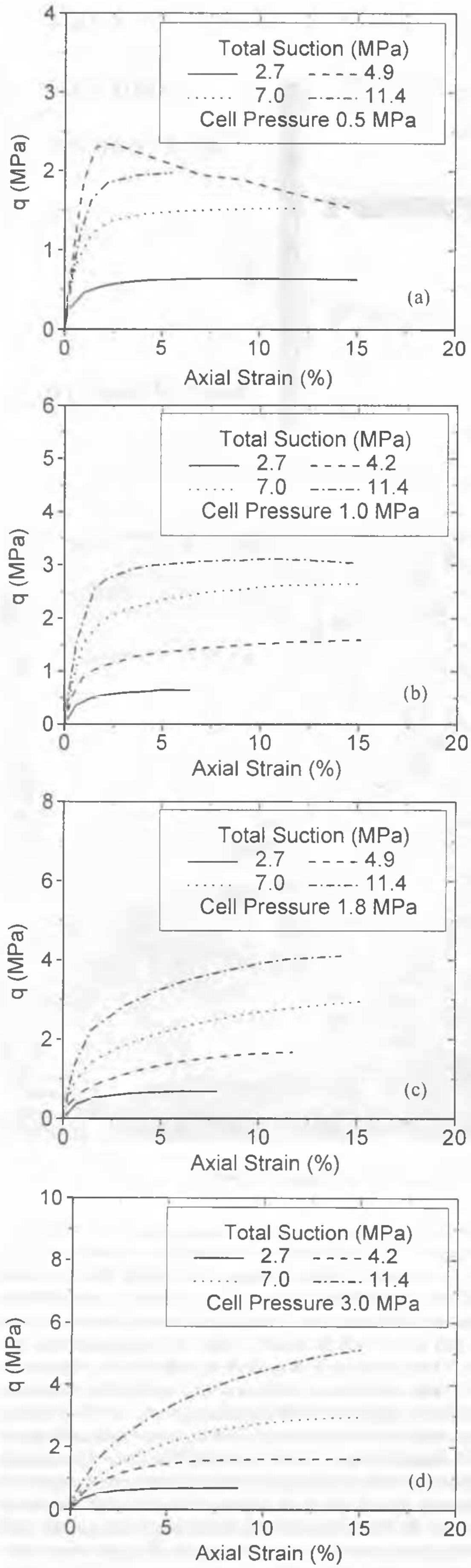

Figure 3 (a) - 3 (d). Stress-strain plots for Series 1 Specimens

4.2 *Impact of Suction on Shear Strength (Series 1)*

Figures 3 (a) to 3 (d) show stress-strain curves for specimens with suctions in the range of approximately 3 – 11 MPa. The figures are plotted for cell pressures of 0.5 MPa, 1.0 MPa, 1.8 MPa, and 3.0 MPa respectively. Shear strengths and stiffness of specimens tested under UU conditions increase with increasing suction. Failure modes were predominantly ductile, except at low saturations and confining pressures where some strain-softening was observed. Brittle failure modes were noted in tests where the suctions were high and confining pressures were low. This is especially evident in Figure 3 (a) for a suction of 11 MPa. Brittle failure occurs immediately after peak strength, followed by strain-softening to approximately 70% of maximum deviator stress. Following failure in the triaxial testing, specimens were removed for visual examination and measurement of water contents.

4.3 *Impact of Suction on Strength and Stiffness (Series 2)*

Figures 4 (a) to 4 (d) show stress strain curves for specimens with different suctions at constant cell pressures of 0.5 MPa, 1.0 MPa, 2.0 MPa, and 3.0 MPa respectively. Results indicate that at low cell pressures, specimens become more brittle with increasing suction. Brittleness is characterized by high peak strengths at approximately 2 – 4 % strain followed by softening to a lower large-strain (or post-peak) strength. This was confirmed by physical inspection that identified well-developed failure planes in the strain-softening (brittle) specimens. At lower suctions and higher confining pressures, specimens failed in a ductile manner and were barrel shaped after removal from the cell. Inspection of the failure planes in brittle specimens revealed smooth glass like striations and grooves, clearly indicating the direction of the failure displacements. Specimens tested at the lowest confining pressure of 0.5 MPa show brittle behaviour most clearly. At 3 MPa confining pressure most specimens failed in a ductile mode.

The stiffness for the specimens was quite consistent, especially for specimens at higher suctions and low confining pressures. Specimens at lower suctions and higher confining pressures showed considerable non-linearity indicating that the material may be yielding whereas the brittle specimens show a relatively linear response until close to the point of failure. The slope of the initial response is broadly similar over the suction range examined.

4.4 *Direct Comparison of Two Testing Series*

Plotting peak strength values for different suction levels as a function of total mean stress at failure (Figure 5) gives a series of strength envelopes that form a failure surface defining a relationship between suction, mean stress, and peak deviator stress. The values of suction vary from 5 MPa to a maximum value of 13 MPa. The graph illustrates increases in peak strength with increasing suction level, and increases in strength due increasing confining pressure.

The suction has a much greater influence on strength than does confining pressure over the range investigated in this program.

Trend lines representing constant suction strength envelopes have been shown to help interpret the relationships. It is apparent that with increasing suction, net mean stress has an increasing influence on the peak strength. At the lower suction range of 5 MPa the envelope appears almost flat, a result that would be expected from a saturated material.

For the lower suction level (5 MPa) it is speculated that compression under the application of cell pressure with no drainage caused the soil structure to compress to the point where specimens were near saturation. This resulted in near $\phi_u=0$ condition due to the undrained loading condition.

At the lower suction values where water contents were simi-

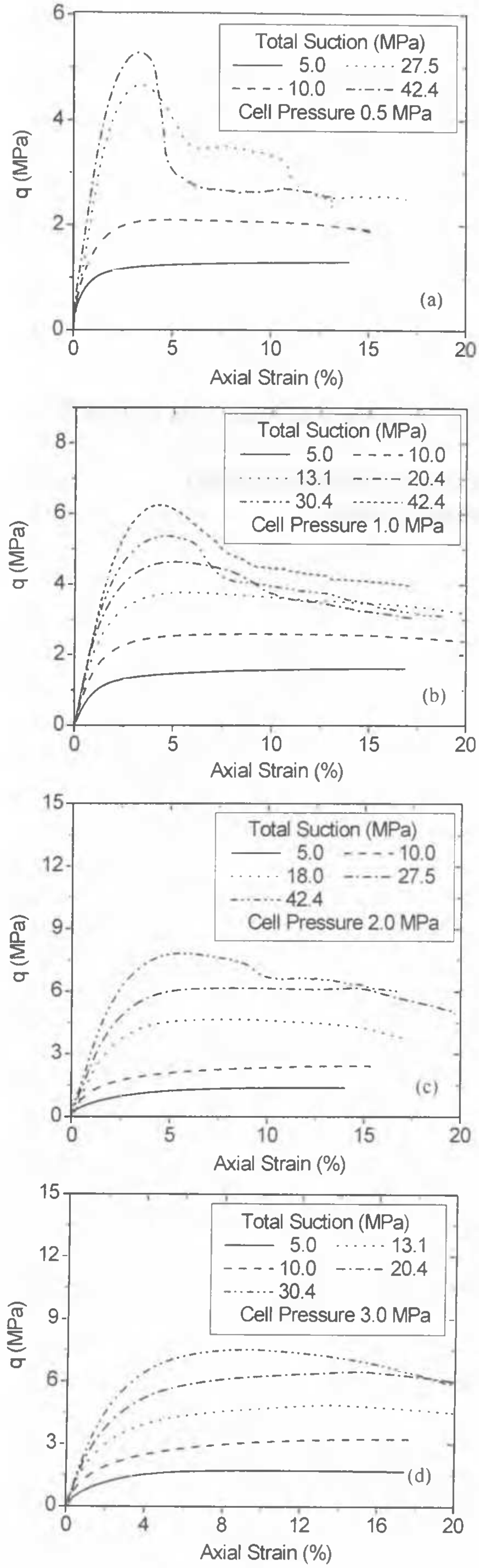

Figure 4 (a) – (d). Stress-strain plots for Series 2 Specimens

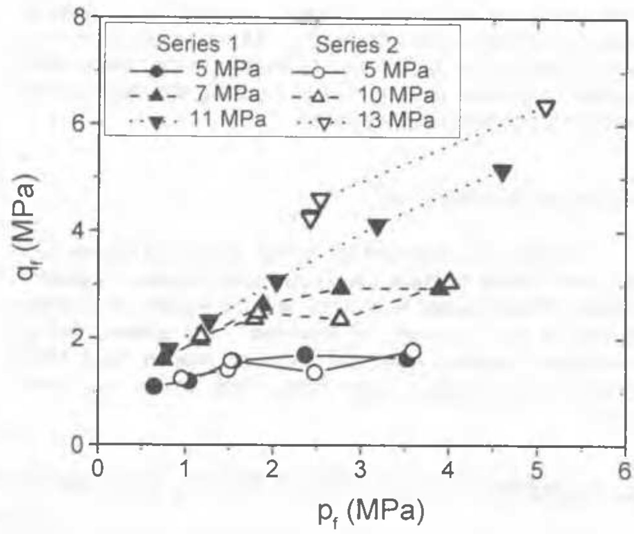

Figure 5 Peak Strength Envelopes for both Series

lar for specimens from both series, the strength values are comparable. At higher suction values, there is a notable difference in the peak shear strength for specimens from the two series. This can be attributed to two factors. Firstly, the suctions are not exactly the same for the specimens being compared from both series due to small inherent variability in preparing the specimens. As a result, specimens in Series 1 have a suction of 11 MPa while the specimens being compared to in Series 2 have a suction of 13 MPa. The second factor that is considered is the difference in dry density associated with the specimen preparation procedure. In the Series 1 specimens, although the water content is altered at the mixing stage to alter the initial suction, all specimens are compacted at the same dry density. In the series 2 specimens, specimens are all compacted to the same density and water content and subsequently dried to lower water contents and higher suctions. The suction increase associated with the phase of preparation immediately prior to shearing results in shrinkage and therefore an increase in dry density. The increase in dry density undoubtedly has an impact on the undrained strength. This is consistent with the increasing variation in strength with increasing suction. The larger the suction increase following compaction in Series 2 specimens, the larger the density increase because of suction induced shrinkage and therefore the larger the strength gain.

5 DISCUSSION AND CONCLUSIONS

Results have been presented from triaxial shearing on two sets of buffer specimens prepared using two different methods to generate initial suctions values. The measured water content - suction curves for the two series of specimens clearly illustrate that for the same constituents at the same water content the suction is not unique - it depends on the molding water content and the drying / wetting history (Tang *et al.* 1998). As a result, comparison of triaxial shearing under undrained conditions shows that the measured strengths at approximately the same suction levels are different for the two series of specimens due to the variation in preparation method. This shows the importance in testing unsaturated soils to develop a specimen preparation procedure that is consistent with the stress and environmental path that the material will be subjected to in the real application.

From a practical standpoint, results from the first series of tests indicates the effect of molding water content on the undrained strength of buffer material compacted to the same dry density. This relationship is useful to determine the optimum molding water content to achieve necessary shear strength for a proposed application.

The second series indicates the change in shear strength associated with suction increase following compaction at a specified target water content and dry density. This relationship is necessary to predict the behaviour of materials where the environmental conditions are expected to decrease the water content following placement of the material.

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REFERENCES

Delage. P. and Graham. J. (1995). Understanding the behaviour of unsaturated soils requires reliable conceptual models. Proc. 1st International Conference on Unsaturated Soils. Paris. France. 1223-1256.

Blatz. J.A. (2000). Elastic plastic modeling of unsaturated high plastic clay using results from a new triaxial test with controlled suction. Ph.D. Thesis. Department of Civil and Geological Engineering, University of Manitoba. (Winnipeg, Manitoba).

Graham. J.. Chandler. N.A.. Dixon. D.A.. Roach. P.J.. To.. T.. Wan, A.W.L. 1997. The buffer container experiment: results, synthesis. issues. AECL Whiteshell laboratories. Pinawa. Manitoba. AECL-11746.

Tang. G.X.. Blatz. J.. Graham. J. (1998). Volume changes in unsaturated sand-bentonite caused by suction controlled drying and wetting. 51st Canadian Geotechnical Conference, Edmonton. Alberta.

Tang. G.X. 1999. Suction characteristics and elastic-plastic modeling of unsaturated sand-bentonite mixture. Department of Civil and Geological Engineering. University of Manitoba. (Winnipeg. Manitoba).

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. (1995). 215-222. eds. E.E.Alonso and P.Delage. publ. Balkema. Rotterdam.

Wheeler. S.J. and Sivakumar. V. 1995. An elasto-plastic critical state framework for unsaturated soil. Geotechnique. **45**(1):35-53.

Wiebe. B.J. 1996. The effect of confining pressure. temperature. and suction on the strength and stiffness of unsaturated buffer. M.Sc. Thesis. Department of Civil and Geological Engineering, University of Manitoba. (Winnipeg. Manitoba).

Wiebe. B.. Graham. J.. Tang. G.X. and Dixon. D. 1998. Influence of pressure. saturation and temperature on unsaturated buffer materials. Canadian Geotechnical Journal. **35**:194-205.

Yarechewski. D.S. (1993) Constant mean effective stress tests on sand-bentonite specimens at elevated temperature. M.Sc. Thesis, Department of Civil Engineering. University of Manitoba. Winnipeg. Manitoba.