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Nonisothermal Shear Strength of Compacted Silt at Residual Saturation

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ABSTRACT: This paper focuses on the results from a new triaxial cell developed to measure the shear strength of unsaturated soils under elevated temperatures and high suction magnitudes. Suction control is implemented by circulating vapor through a soil specimen having an initially low degree of saturation while the temperature of the soil specimen is controlled using heating elements within the cell fluid. A mechanical load frame was also modified to be capable of performing both load and constant displacement control triaxial tests. Volume changes were assessed using axial displacements and by tracking changes in the cell fluid volume. In addition to presenting the details of the new cell, the results from a set of drained triaxial tests performed on compacted silt specimens under different combinations of total suction and net normal stress at both ambient and elevated temperatures are presented.

INTRODUCTION

An understanding of the thermo-hydro-mechanical behavior of unsaturated soils during application of elevated temperatures and high suction magnitudes is needed to interpret the behavior of many thermally active geotechnical systems. Examples of these systems that often include unsaturated soils are ground-coupled heat exchangers, heat dissipation embankments, containment systems for nuclear waste, and buried electrical cables (McCartney 2012). Heating of unsaturated soils may cause both volume changes as well as drying, both of which may affect the shear strength and stiffness. Although some studies have evaluated the impact of high suction magnitudes on the shear strength and volume change (Blatz & Graham 2000; Nishimura & Fredlund 2000; Lloret et al. 2003) and others have evaluated the impact of elevated temperatures on these variables (Saix et al. 2000; Uchaipichat & Khalili 2009), the combined effects of temperature and high suction magnitudes have not been investigated. An understanding of the inter-relationships between high suction and temperature will also provide validation data for nonisothermal elasto-plastic constitutive relations used to describe the behavior of unsaturated soils. Although a range of thermo-elasto-plastic constitutive relationships have been developed for saturated soils (Baldi et al. 1998; Hueckel & Baldi 1990, Laloui & Cekerevac 2003, Abuel-Naga et al. 2009, Hueckel et al. 2009), only a few have been developed for unsaturated soils under nonisothermal conditions (Bolzon and Schrefler 2005), albeit without consideration of the effects of high suctions.

The objective of this paper is to present a new triaxial cell used to evaluate the the nonisothermal shear strength and deformation behavior of unsaturated soils under high suction magnitudes. The triaxial cell was designed which incorporates the vapor flow technique developed by Likos & Lu (2003) to control high suction magnitudes. Further, the triaxial cell builds upon the experience of Uchaipichat & Khalili (2009) for nonisothermal testing by including a set of resistance heaters in a glass cell, cell fluid circulation, and redundant approaches to measure specimen volume change.

BACKGROUND

Vapor Equilibrium Technique for Control of High Suction Magnitudes

The vapor equilibrium technique is a common approach to control the total suction in unsaturated soils (Delage et al. 1999; Blatz & Graham 2000; Tang and Cui 2005). This technique involves uses saturated salt solutions to control the relative humidity of the air within a closed environmental chamber. Water from the pores of a soil specimen within the chamber will evaporate or condense to reach equilibrium. The basis of this technique is Kelvin’s law, which relates the total suction to the relative humidity of the pore air, as follows:

$$\psi = \frac{\rho_w R T}{M_w} \ln\left(\frac{R_h}{100}\right) \qquad (1)$$

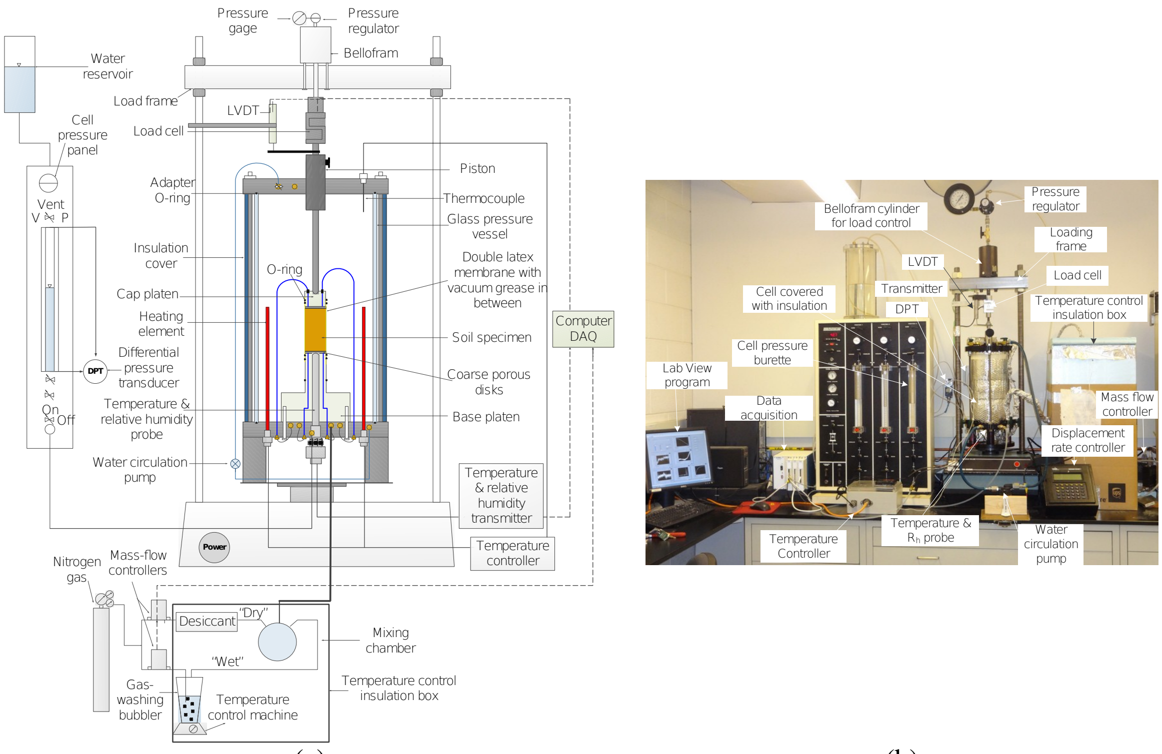
where ψ = the total suction (kPa), R = the universal (molar) gas constant, equal to 8.31432 J/molK, T = the absolute temperature in Kelvin, M_W = the molecular mass of water vapor equal to 18.016 g/mol, ρ_w = the density of water (kg/m^3), and R_h = the relative humidity of the pore air in percent.

Several studies have incorporated the vapor equilibrium technique into triaxial cells (Blatz & Graham 2000; Nishimura & Fredlund 2003), but only under ambient room temperature conditions. The vapor equilibrium technique is very sensitive to air temperature (Tang & Cui 2005; Alsherif & McCartney 2012), which combined with the slow rates of evaporation and condensation and changes in solubility of salt with temperature make the vapor equilibrium technique unsuitable for studying the independent effects of suction and temperature on soils. An alternative approach based on similar principles is the vapor flow technique proposed by Likos & Lu (2003). This technique involves control of the relative humidity of gas flowing through a soil specimen by using a pair of mass flow controllers to mix water-saturated and dry air to different proportions before passing it through the soil. The advantages of this approach over existing suction measurement techniques are that it is automated, has a broader measurement range, and can be used to determine both wetting and drying behavior in a shorter time than the vapor equilibrium technique.

TESTING APPARATUS

Triaxial Cell

The new triaxial cell was designed to accommodate the application of high suction magnitudes using an automated humidity system with continuous gas flow as well as elevated temperatures. A drawing and picture of the modified triaxial cell with its different components are shown in Figures 1(a) and 1(b), respectively. Duran Borosilicate glass tubing having an outer diameter of 180 mm, a wall thickness of 9 mm and a length of 381 mm was used as the pressure vessel for the triaxial cell. This material was selected because the ultimate use of the triaxial cell is to evaluate the nonisothermal shear strength of soils under high suction magnitudes (Alsherif and McCartney 2013). This glass has a high resistance to thermal shock, a low coefficient of thermal expansion, low creep potential, and high chemical resistance. The main shortcoming is that internal pressures are limited to 630 kPa.



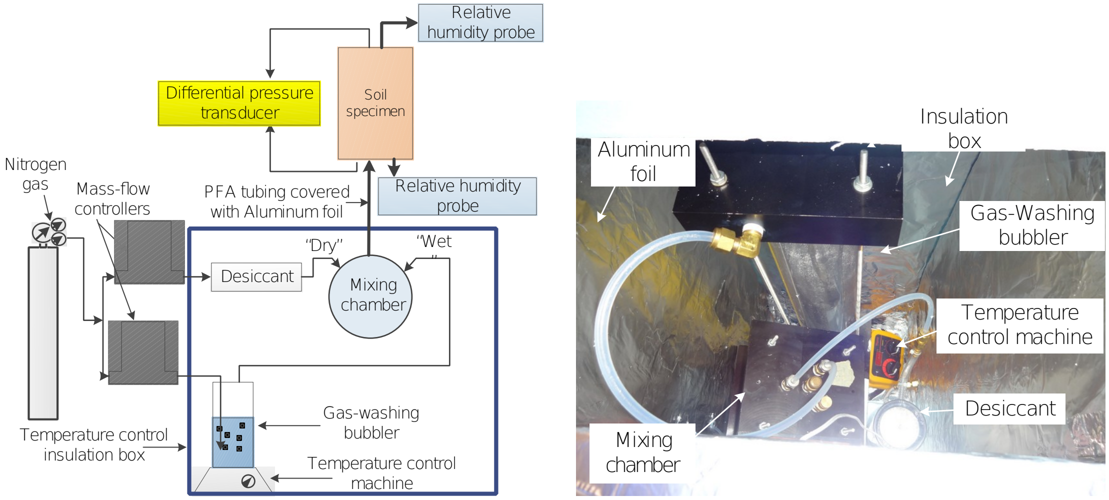
(a) (b)

Figure 1: Thermo-hydro-mechanical triaxial setup for testing soils under high suction magnitudes: (a) Schematic; (b) Picture

Suction Control System

A schematic and picture of the automated humidity-control system are shown in Figures 2(a) and 2(b), respectively. The relative humidity is controlled using a pair of computer-controlled proportional mass-flow valves (MKS Instruments, Type 1179A) to partition the vapor-saturated, or 'wet', Nitrogen gas and desiccated, or 'dry', Nitrogen gas to a mixture with a desired target relative humidity. These valves can regulate the flow of each gas stream between zero and 3.3×10^{-6} m^3/s. Nitrogen is passed from a pressure-regulated bottle through 6.3 mm-diameter perfluoroalkoxy (PFA) tubing to each of the valves to create two gas streams. The first gas stream is vapor-saturated by passing it through a bubbling tank filled with distilled water. The tank is placed on a hot plate so that the gas has the same target temperature as that being applied to the soil specimen. The second gas stream is routed through a

Hammond cylinder filled with drierite desiccant to create zero relative humidity gas. The wet and dry gas streams are reintroduced into a mixing chamber at the same flow rate. The system is contained within an insulated box to maintain the same temperature at the soil specimen.



(a) (b)

Figure 2: The vapor flow technique for suction control: (a) Schematic, (b) Picture of the components inside the insulation box

The combined gas stream, having a relative humidity that is a direct function of the 'wet' to 'dry' gas flow ratio (w/d), is forced through the bottom and vented from the top of the soil specimen. After reaching steady-state gas flow through the specimen, the relative humidity of the gas is adjusted using a feedback-control system that monitors the relative humidity and temperature measured by a probe that is flush-mounted with the base of the specimen (Model HMT330 from Vaisala, Inc.). A rigid porous disk separates the bottom of the specimen from the head of the probe to avoid the any possible influence of the probe on the mechanical behavior of the specimen. The top of the specimen is connected to an insulated bottle containing a sensor to monitor the relative humidity of the gas vented from the top of the specimen, which was vented to the atmosphere (i.e., zero air pressure). When the relative humidity values of the inlet and outlet gases are the same, then the specimen is assumed to be in equilibrium with a total suction predicted using Eq. (1). This assumption is based on the idea that constant relative humidity is applied to the bottom of soil specimen and the flow of gas one-dimensional from the bottom to the top of specimen. This means that the decrease in relative humidity progresses upward through the specimen until equilibration occurs. In addition, a differential pressure transducer (DPT) connected to the top and bottom of soil specimen is used to monitor the differential pressure across the specimen. As the pressure at the base was 40 kPa while the pressure was 0 kPa at the top, the average air pressure in the specimen was 20 kPa.

Temperature Control System

A temperature controller connected to three Watlow cartridge-type heating elements in the base of the cell is used to control the temperature of the cell fluid, with a thermocouple at the top of the cell used to provide feedback. To ensure that the temperature of the pressurized water in the cell is uniform, a pump (Model TS5 15PV from TopsFlo) is used to circulate the water from the top to the bottom. The pump is capable of operating under pressures up to 1000 kPa and temperatures up to 100 °C.

Mechanical loading system

A Brainard-Kilman Model S-600 triaxial load frame was adapted to apply loads to the triaxial cell in either load-control or displacement-control conditions. In normal operation, this load frame can be used to apply constant displacement rates to shear a soil specimen. In addition, a pneumatic piston was incorporated into the top beam of the triaxial cell to apply load-controlled conditions to the specimen. Load-controlled conditions allow the soil specimen to deform freely in the axial direction during changes in suction or temperature. In either configuration, a load cell is used to record axial loads applied to the specimen. The axial displacement during all stages of suction application, heating and shearing is measured using a linearly variable differential transformer (LVDT) connected to the top piston. Volume changes of the soil specimen due to changes in suction, temperature, or shearing are monitored by tracking the water level in a burette connected to the cell pressure using a differential pressure transducer. Calibration tests were performed to quantify the impact of cell pressure and temperature on this system (Alsherif and McCartney 2013).

Test Materials and Specimen Preparation

ML silt obtained from the Bonny Dam on the Colorado-Kansas border was used in this experimental study. The silt, which has a specific gravity of 2.65, was statically compacted using a press to a dry unit weight of 15.7 kN/m^3 and initial degree of saturation of 0.41. Prior to compaction, the soil was oven-dried at a temperature of 110 °C for 24 h, the crushed and screened through a No. 40 sieve. It was then wetted to an initial water content of 10.5% and placed in a sealed plastic bag to homogenize for 24 hours. The soil was compacted using a mechanical press in three lifts having thicknesses of 24 mm in a 35 mm-diameter model. The interfaces between lifts were scarified using a blade. Specimens were prepared at an initial void ratio of 0.68, and a compaction water content of 10.5% (8% dry of optimum). The low compaction water content was selected so that the initial degree of saturation was low enough to have continuous air voids through the specimen. In this case, the air permeability should be high enough to permit rapid suction equilibration in the vapor flow technique.

Specimen Setup and Test Procedures

Coarse porous stones and filter paper were placed at the top and bottom of the specimen, after which two 0.635 mm-thick rubber membranes, separated by a layer of vacuum grease, were placed around the specimen. Next, the cell was filled with de-aired water at room temperature, a seating confining pressure was applied, and the cell water circulation pump was started. A constant axial load was applied to the top of the soil specimen to permit measurement of the axial deformations during heating and suction application, and the specimen was consolidated to the target cell pressure. Two different testing paths shown in Figure 3 were followed to investigate the influence of temperature on unsaturated silt behavior. The first testing path was to increase temperature up to a target value of 65˚C after applying the confining pressure, and then use the vapor flow technique to impose a suction on the soil specimen (Path 1, ABCD). The second testing path was to bring the soil specimen to suction equilibrium at room temperature, and then increase the temperature up to a target value in stages (Path 2, ABEFGD).

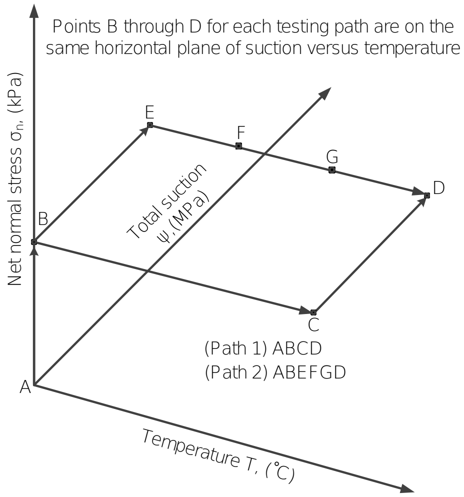
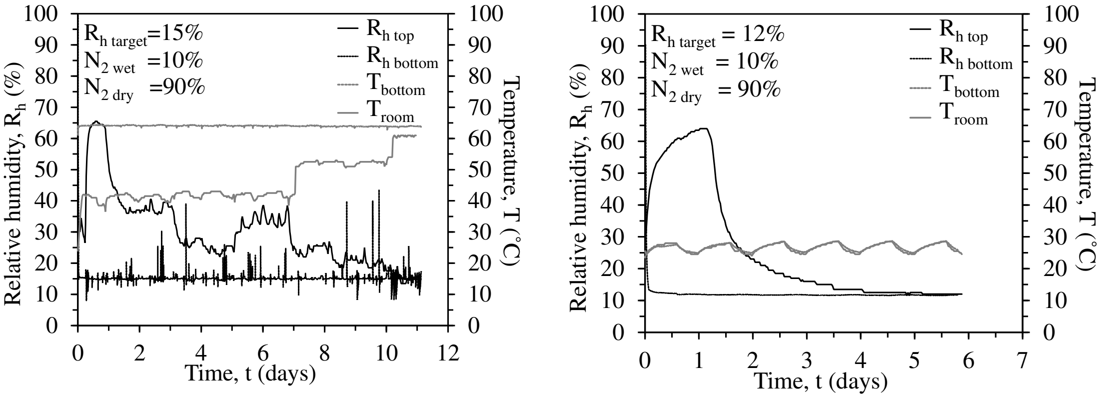


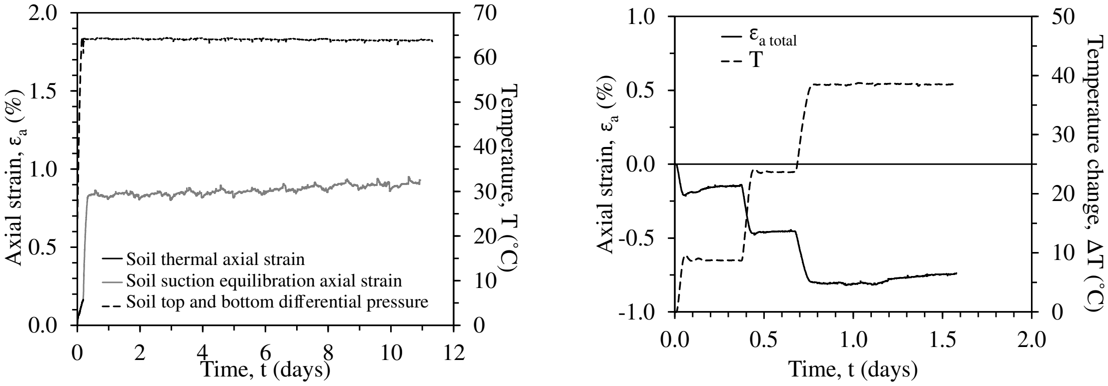
Figure 3: Testing paths investigated for suction and temperature control

In either testing path, the automated humidity control system was used to apply a specified value of total suction to the specimen. The relative humidity and temperature at the bottom and top of the specimen during suction equilibrium following Paths 1 and 2 are shown in Figures 4(a) and 4(b), respectively. Two hours were needed for the relative humidity at the bottom ($R_{h\ bottom}$) to reach the target value ($R_{h\ target}$), while an average of one to two weeks was needed for the relative humidity at the top ($R_{h\ top}$) to reach the same target value. After the target relative humidity at the top of the specimen was attained, at least six additional hours were allowed to ensure uniformity of total suction throughout the soil specimen along with attaining constant differential pressure across the soil specimen using DPT connected between top and bottom of the specimen. The soil specimen was assumed to be in equilibrium under the externally applied stresses and internally applied suction when the axial deformations remained constant for at least 24 hours, as shown in Figure 5(a). After suction equilibration for Path 2, sufficient time was allowed for equilibration during each increase in temperature before finally shearing the specimen at point D in Figure 3. The axial strain was continuously monitored as shown in Figure 5(b).



(a) (b)

Figure 4: Vapor flow measurements: (a) Relative humidity and temperature for a specimen under a net confining pressure of 300 kPa for Path 1; (b) Relative humidity and temperature under a net confining pressure of 200 kPa for Path 2



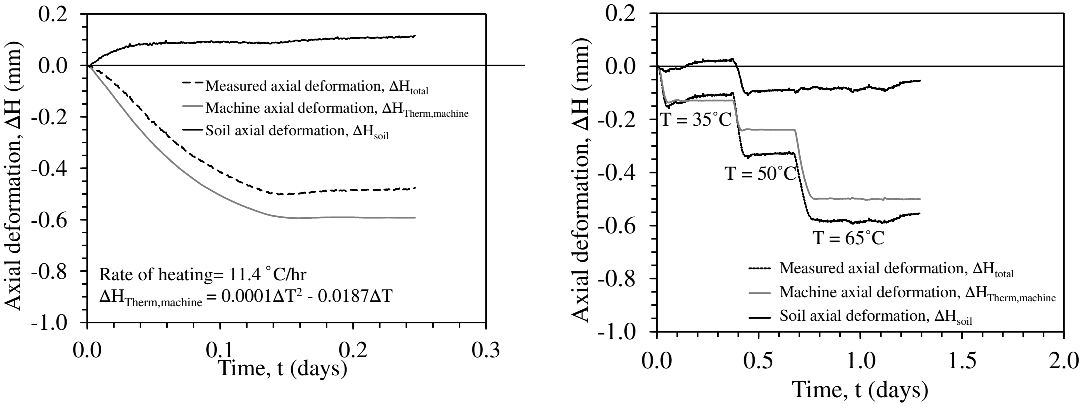
(a) (b)

Figure 5: Axial strain during suction application: (a) Net confining stress of 300 kPa for Path 1; (b) Net confining stress of 200 kPa for Path 2

After the soil reaches equilibrium, the load frame was switched from load- to displacement-control conditions. A constant displacement rate of 1.27×10^{-4} m/min was applied to shear the soil specimen, which was found to ensure drained conditions (i.e., no change in relative humidity was measured). The relative humidity control system continued to operate during shearing to ensure constant suction conditions.

RESULTS

To account for machine deflections, a set of calibration tests under the same testing paths shown in Figure 3 were performed on an aluminum specimen having the same dimensions of the soil specimen. The calibration results for thermal axial deformation were subtracted from the test measurements to obtain the deformations of the soil. The soil axial deformations in Figure 6(a) for Path 1 indicate that the soil contracted during the heating process. The soil axial deformations in Figure 6(b) for Path 2 indicate that the soil has a contractive behavior during the first increase in temperature, followed by expansive behavior for higher temperatures.



(a) (b)

Figure 6: Machine corrections to the measurements of axial deformation: (a) Net confining stress of 300 kPa and temperature of 65°C following Path 1; (b) Net confining stress of 200 kPa and temperature of 65°C following Path 2

The thermal axial strains over a change in temperature of 40°C for different testing paths and confining pressures are presented in Figure 7. For tests performed following Path 1, the results indicate that the increase in confining pressure causes the compacted silt to show more contractive behavior. This contractive behavior is consistent because the soil in this test was heated under the initial degree of saturation of 41% before application of high suction. In this case, heating the soil causes an excess pore water pressure generation causing the soil to expand at the beginning of heating under lower confining pressure. Under drained conditions, dissipation of pore water pressure caused contraction with further increases in temperature. The reason that the results from Path 2 differed from those of Path 1 is that when application of a high suction to a soil specimen leads to an increase in effective stress and a reduction in volume. This will cause the soil to behave like an overconsolidated soil in saturated conditions and expand during heating (Uchaipichat and Khalili 2009).

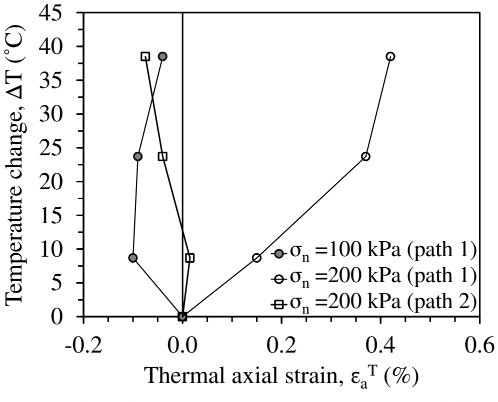
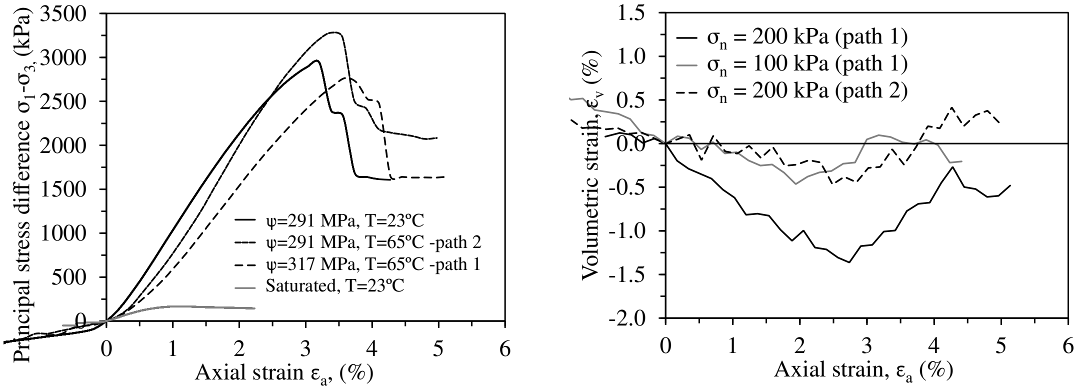


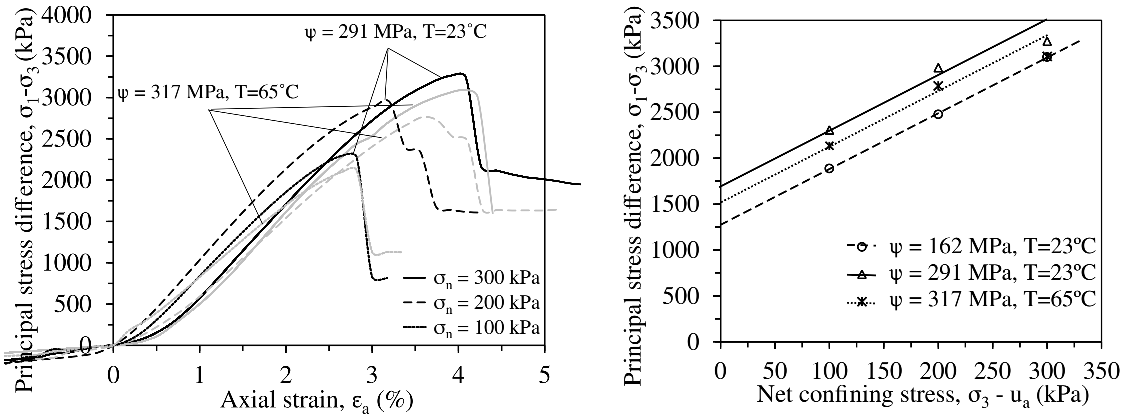
Figure 7: Thermal axial strains for Paths 1 and 2 under different net confining stresses

For either testing path, after reaching a temperature of 65°C and a constant suction value of 291 MPa (corresponding to a degree of saturation of 0.11), a consolidated drained triaxial test was performed at net confining stresses of 100, 200 and 300 kPa following Path 1 to define the failure envelope. One consolidated drained triaxial test was performed following Path 2. The stress-strain curves measured during shearing of the specimens that had reached equilibrium under a temperatures of 23 and 65°C following the different testing paths are shown in Figure 8(a) for a mean confining stress of 200 kPa. The results from saturated specimens at room temperature are also shown in the figure for comparison. The results clearly indicate that the maximum principal stress difference decreases with temperature for the specimen tested following Path 1, and increases with temperature for the specimen tested following Path 2. This behavior is currently being investigated using thermo-elasto-plastic constitutive models. A brittle failure mode was observed in the stress-strain curves for all specimens under high suction magnitudes regardless of temperature effect, which differed significantly from the relatively smooth stress-strain curves of the saturated specimens. The volumetric strain during shearing of the unsaturated specimens is shown in Figure 8(b). The results indicate that relatively dry soil dilates during shearing following Path 1, and that dilation increases with increasing net confining stress. The specimen sheared following Path 2 experienced less dilation under the same confining pressure. The results from tests following Path 1 for different mean confining stresses are shown in Figure 9(a). A decrease in shear strength was observed with increasing temperature for all three confining stresses. The failure envelopes for the different suctions and temperatures are shown in Figure 9(b), which indicate that the peak friction angle is not affected by temperature or suction, and only the apparent cohesion changes.



(a) (b)

Figure 8: Shear test results for Bonny silt for Paths 1 and 2: (a) Stress-strain curves at net confining stress of 200 kPa; (b) Volumetric strain versus axial strain



(a) (b)

Figure 9: Shear test results following Path 1 at different confining stresses: (a) Stress-strain curves; (b) Failure envelopes

CONCLUSIONS

Drained heating of unsaturated soils under high suction magnitudes was found to result in thermal volumetric contraction or expansion of the soil based on the initial overconsolidation ratio of the specimen. The impact of temperature on the shear strength of unsaturated soils was found to depend on the testing path followed. If a suction value was imposed after heating, the shear strength was observed to decrease by 10% for a change in temperature of 40°C from room temperature. If a suction value was imposed before heating, the shear strength was observed to increase by 20% for a change in temperature of 40 °C from room temperature.

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REFERENCES

Abuel-Naga, H.M., Bergado, D.T., Bouazza, A., and Pender, M. (2009). "Thermomechanical model for saturated clays." Géotechnique. 59(3), 273–278.

Alsherif, N. and McCartney, J.S. (2013). "Triaxial cell for nonisothermal shear strength of compacted silt under high suction magnitudes." 1st Pan-American Conf. on Unsaturated Soils. February 20-22, 2013. Cartagena de Indias, Colombia. 6 pg.

Baldi, G., Hueckel, T., and Pellegrini, R. (1988). "Thermal volume changes of the mineral-water system in low-porosity clay soils." Can. Geotech. J. 25: 807–825.

Blatz, J.A. and Graham, J. (2000). "A system for controlled suction in triaxial tests." Géotechnique 50(4):465–478

Bolzon, G. and Schrefler, B.A. (2005). "Thermal effects in partially saturated soils: A constitutive model." Int. J. Numer. Anal. Meth. Geomech. 29, 1-17.

Delage, P., Cui, Y.J., Yahia-Aissa, M. and De Laure, E. (1998). "The unsaturated hydraulic conductivity of a dense compacted bentonite." 2nd Int. Conf. on Unsaturated Soils. Beijing, China. pp. 27–30

Hueckel, T., and Baldi, M. (1990). "Thermoplasticity of saturated clays: experimental constitutive study." Journal of Geotechnical Engineering, 116(12), 1778–1796.

Hueckel, T., François, B. and Laloui, L. (2009). "Explaining thermal failure in saturated clays." Géotechnique. 59(3), 197–212.

Laloui, L. and Cekerevac, C. (2003). "Thermo-plasticity of clays: an isotropic yield mechanism." Computers and Geotechnics. 30(8), 649–660.

Likos, W. and Lu, N. (2003). "Automated humidity system for measuring total suction characteristics of clay." Geotechnical Testing Journal, 26(2),

Lloret, A., Villar, M.V., Sanchez, M., Gens, A., Pintado, X., and Alonso, E.E. (2003). "Mechanical Behaviour of Heavily Compacted Bentonite under High Suction Changes." Géotechnique. 53(1), 27-40

McCartney, J.S. (2012). "Issues involved in using temperature to improve the mechanical behavior of unsaturated soils." 5th Asia-Pacific Unsaturated Soils Conference. February 29-March 2, 2012. Pattaya, Thailand. 6 pg.

Nishimura, T. and Fredlund, D. G. (2000). "Relationship between shear strength and matric suction in an unsaturated silty soil." Proc. UNSAT Asia. Singapore, May 18-19, 563-568.

Saix, C., Devillers, P., and El Youssoufi, M.S. (2000). "Element de couplage thermomechanique dans la consolidation de sols non satures." Can. Geotech. J. 37, 308-317.

Tang, A. M. and Cui, Y. J. (2009). "Modelling the thermomechanical volume change behaviour of compacted expansive clays." Géotechnique. 59(3), 185–195.

Uchaipichat, A. and Khalili, N. (2009). "Experimental investigation of thermo-hydro-mechanical behaviour of an unsaturated silt." Géotechnique 59(4), 339–353.