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High Pressure Triaxial Cell for Thermal Volume Change Measurements of Unsaturated Soils

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ABSTRACT: This study focuses on a new experimental approach to characterize the thermal volume change of unsaturated soils under different stress states. Specifically, a thermal triaxial cell was constructed with suction control using the axis translation technique, saturation control using a flow pump, cell pressure control using a high pressure flow pump, and a metal cell to permit application of net mean stresses up to 10 MPa. The cell was constructed to measure the thermal volume change of unsaturated soils under high degrees of saturation (continuous water phase) while precisely tracking the total soil volume and pore water outflow/inflow volumes, in addition to measuring the impacts of suction and temperature on preconsolidation stress. The thermal triaxial cell is also capable of applying anisotropic stress states, with the axial stress controlled using a pneumatic Bellofram piston. This paper presents the thermo-mechanical calibration data along with the results from a test on an unsaturated silt specimen. The thermal volume change of the specimen up to a temperature of 40 °C was consistent with results from the literature for normally consolidated conditions.

1 INTRODUCTION

The thermal volume change of unsaturated soils is gaining interest due to the incorporation of ground source heat exchangers into geotechnical engineering infrastructure. Examples of such applications involving unsaturated soils and elevated temperatures include energy foundations (Murphy et al. 2014), thermally active soil embankments (Coccia and McCartney 2013), and thermally active mechanically-stabilized earth (MSE) walls (Stewart et al. 2014). Although testing equipment and procedures have been developed to characterize the volume change of unsaturated soils (Uchaipichat et al. 2011), challenges still remain in the measurement of thermal volume changes under different stress states and the associated changes in mechanical behavior.

Although several studies have evaluated the thermal volume change of unsaturated soils under different values of matric suction and net stress (Romero et al. 2005; Tang et al. 2008; and Uchaipichat and Khalili 2009; among others), the role of preconsolidation stress has not been thoroughly evaluated. The preconsolidation stress plays an important role in the behavior of both saturated and unsaturated soils (Eriksson 1989; Tidfors and Sällfors 1989; François et al. 2007). A deeper understanding of this topic will help in the development and calibration of thermo-elasto-plastic constitutive models for unsaturated soils.

The objective of this paper is to develop and characterize a new thermal triaxial cell capable of measuring the thermal volume change of unsaturated soils under isotropic and anisotropic stress states. A high pressure flow pump is used to track the volume of cell fluid and to control the cell pressure regulated by a pressure feedback-control loop. Matric suction is controlled using the axis-translation technique (Hilf 1956), and the degree of saturation is tracked using another flow pump operated in suction feedback-control conditions (McCartney and Znidarčić 2010). Elevated temperatures are applied to a soil specimen by heating the cell water using cartridge heaters installed within the cell. The cell was designed to evaluate the compression behavior of unsaturated soils up to stresses of 10 MPa before and after heating in strain-controlled conditions. This paper presents the thermo-mechanical machine deformations of the thermal triaxial cell along with thermal volume change results from a drained heating test on normally consolidated unsaturated silt.

2 BACKGROUND

2.1 *Effective Stress in Unsaturated Soil*

The effective stress for unsaturated soils may be expressed using the approach of Bishop (1959):

$$\sigma' = \sigma_n + \chi\psi \quad (1)$$

where σ_n is net stress, ψ is suction, and χ is an effective stress parameter used to define the influence of matric suction on effective stress.

The performance and accuracy of the effective stress approach relies heavily on the definition of χ. Bishop (1959) proposed χ to be equal to degree of saturation. However, Zerhouni (1991) found χ = S overestimated the effective stress parameter for drier soils (S < 30%) and underestimated for wetter soils (S > 70%). Khalili and Khabbaz (1998) proposed a non-linear relationship between χ and the ratio of matric suction over a constant suction transition value ψ_e (known as the suction ratio), as follows:

$$\chi = \begin{cases} 1 & \text{if } \psi < \psi_e \\ \left(\dfrac{\psi}{\psi_e}\right)^{-\Pi} & \text{if } \psi < \psi_e \end{cases} \tag{2}$$

In Eq. 2, the suction transition value ψ_e can be defined as the air entry suction ψ_{ae} or the air expulsion suction ψ_{ex}, depending on whether the soil is undergoing drying or wetting, and Π is a model fitting parameter used to define the influence of the suction ratio on the effective stress parameter. Khalili and Khabbaz (1998) found that Π = 0.55 fits most experimental data from the literature with lower and higher values occurring for coarse-grained and fine-grained soils, respectively.

2.2 *Thermal Effects on Volume Change*

Heating of a soil specimen in drained conditions can lead to both recoverable (elastic) and irrecoverable (plastic) volumetric strains (Campanella and Mitchell 1968). During drained heating tests on normally consolidated and lightly overconsolidated saturated soils, the differential expansion of water and soil particles leads to a generation of excess pore water pressure, which dissipates with time, resulting in an elasto-plastic volumetric contraction of the bulk soil (Campanella and Mitchell 1968; Delage et al. 2000). For soils with overconsolidation ratios (OCRs) greater than 1.5 to 3, elastic thermal expansion is typically observed (Cekerevac and Laloui 2004).

Similar behavior has been observed for unsaturated soils (Tang et al. 2008; Uchaipichat and Khalili 2009). Uchaipichat and Khalili (2009) performed drained heating tests on compacted silt specimens at suctions of 0, 100, and 300 kPa at different net confining stresses (50, 100, 150, and 200 kPa). Their results, along with those from Tang et al. (2008) were re-interpreted in terms of OCR using the definition of effective stress proposed by Khalili and Khabbaz (1998), and are presented in Figure 1. Reversible thermal expansion was observed for specimens at lower net confining stress (i.e. higher OCR) with larger irreversible thermal contraction under lower net stresses (i.e., lower OCR). Further, for a given net stress, the amount of thermal contraction increased with increasing suction.

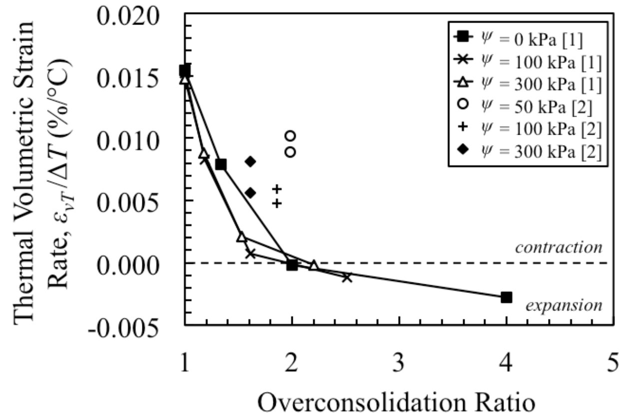


Figure 1. Ratio of thermal volumetric strain to temperature change: [1] Uchaipichat and Khalili (2009); [2] Tang et al. (2008)

2.3 *Thermal Effects on Preconsolidation Stress*

Several authors have studied the influence of temperature on effective preconsolidation stress by heating overconsolidated soil specimens, then loading the specimen under constant temperature (Eriksson 1989; Tidfors and Sällfors 1989; François et al. 2007). Results from these tests on saturated soil indicate that preconsolidation stress decreases with increasing temperature (FIG. 2). Tidfors and Sällfors (1989) observed a linear decrease in effective preconsolidation stress with temperature, while a logarithmic relationship has been suggested by others (Eriksson 1989; Cekerevac and Laloui 2004; François and Laloui 2008).

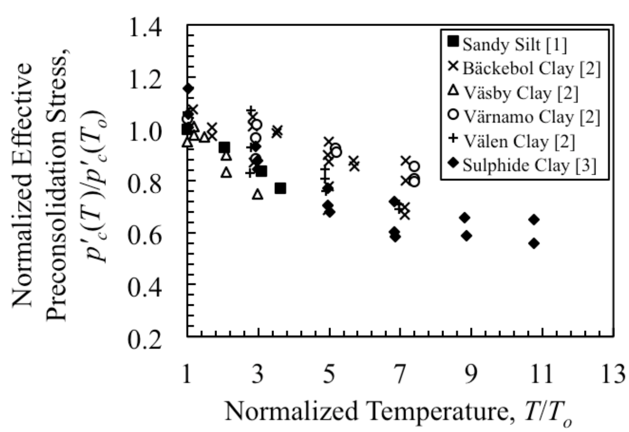


Figure 2. Influence of temperature on normalized effective preconsolidation stress for saturated soils [1] François et al. 2007; [2] Tidfors and Sällfors (1989); [3] Eriksson (1989)

Different behavior has been observed for saturated soil specimens heated under normally consolidated conditions and then loaded isothermally (Towhata et al. 1993; Sultan 1997). Sultan (1997) loaded a sample of Boom clay to normally consolidated conditions at a constant temperature of 20 °C and then heated the sample to 70 °C. Following heating, the sample was loaded until reaching normally consolidated conditions. An increase in effective preconsolidation stress from 0.8 to 1.12 MPa was observed, indicating a potential "overconsolidation" effect.

2.4 *Suction Effects on Preconsolidation Stress*

Effective preconsolidation stress also increases with increasing matric suction (Salager et al. 2008; Uchaipichat and Khalili 2009). Uchaipichat and Khalili (2009) performed temperature and suction controlled isotropic loading tests on a compacted silt for different values of matric suction (0, 100, and 300 kPa) and temperature (25, 40, and 60 °C). The effective preconsolidation stress of each silt specimen was observed to remain constant for suction values less than that of the air entry suction, as expected for saturated soils (Khalili et al. 2004). However, once the air entry suction was exceeded, the soil entered unsaturated conditions and p'_c increased with increasing applied matric suction (FIG. 3). Similar behavior has been observed by Salager et al. (2008) who suggested a logarithmic relationship between effective preconsolidation stress and matric suction. The results of Uchaipichat and Khalili (2009) are summarized in Figure 3. In addition to an increase in p'_c with matric suction, the rate of increase may vary with temperature.

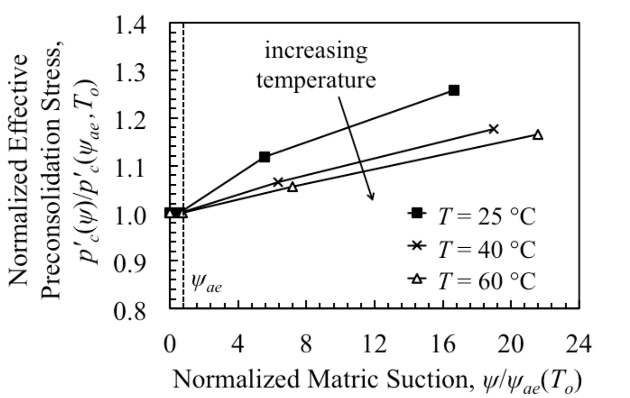


Figure 3. Nonisothermal relationship between normalized preconsolidation stress and suction (Uchaipichat and Khalili 2009)

3 EXPERIMENTAL SETUP

A new triaxial cell was designed to control and measure elevated temperatures and low suction magnitudes. A schematic of the thermal triaxial cell system is shown in Figure 4(a) and a photo is shown in Figure 4(b). The cylindrical vessel is made of aluminum 6061-T6511 with an outside diameter of 165.1 mm, a wall thickness of 9.5 mm, and a height of 304.8 mm. The cell can accommodate specimens having a height up to 127 mm and a diameter up to 63.5 mm, so the cell may be used for volume change measurements on short specimens or for shear strength measurements on specimens having a 2:1 height:diameter ratio.

The aluminum alloy vessel is anodized for corrosion resistance and can accommodate net cell pressures to 10 MPa. The top and base of the triaxial cell are made of 316 stainless steel. The capability of the thermal triaxial cell to withstand high pressures allows for a broad range of overconsolidation ratios and initial suction/saturation conditions to be achieved via various combinations of applied net stress and matric suction paths. Further, a larger range of cell pressures will permit the assessment of changes in effective preconsolidation stress due to changes in temperature and matric suction, even at higher suction magnitudes which may cause the effective preconsolidation stress to exceed the capacity of most conventional triaxial devices.

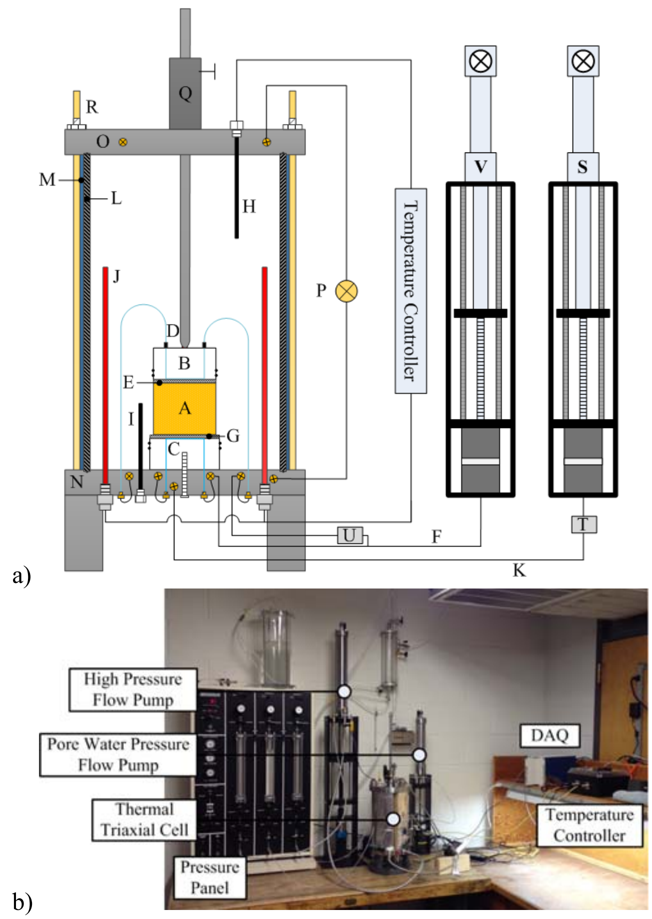


Figure 4. Thermal triaxial cell: (a) Schematic, [A] Soil specimen [B] Top platen [C] Bottom platen [D] Air pressure line [E] Course porous stone [F] Water inlet line [G] HAE ceramic disk [H] TC probe to DAQ [I] TC probe to temperature controller [J] Heating cartridge [K] Cell pressure line [L] Aluminum chamber [M] Insulation [N] Stainless steel base [O] Stainless steel top [P] Water circulation pump [Q] Rod and bearing assembly [R] Mounting rods [S] High pressure flow pump [T] Pressure sensor [U] Differential pressure transducer (DPT) for matric suction monitoring [V] Pore water pressure flow pump; (b) Photograph

3.1 *Suction Control System*

The top and bottom platens were designed to allow independent application of water and air pressure to the soil specimen following the axis-translation technique (Hilf 1956). The pore water pressure is controlled via a 7 mm-thick, 71.1 mm-diameter high air entry value (HAEV) ceramic disk placed between the bottom platen and the soil specimen. The HAEV disk has a rated air entry value of 100 kPa. Pore air pressure is controlled at the top of the specimen using a 7 mm-thick, 63.5 mm-diameter coarse porous beneath the top platen to ensure a uniform application of air pressure to the top of the specimen.

Pore air and water pressures are initially applied to the specimen through two independent burettes mounted to a Trautwein Control Panel (FIG. 4b). Following initial saturation, the top air pressure line is flushed of water and the bottom pore water pressure is controlled using a flow pump (FIG. 4a/b) that operates by moving a circular piston with a cross-sectional area of 792 mm^2 in or out of a reservoir. Movement of the piston during testing is controlled and monitored by a stepper motor (Model STX-115-07 from Copley Control Corp.) with a velocity range of 0.00001 to 5 mm/s. Operation of the flow pump results in changes in pore water pressure and matric suction at the base of the specimen. Suction is maintained using a feedback control loop incorporating a 140 kPa Validyne (Model P305D) differential pressure transducer (DPT) which is connected to the outgoing water and air pressure lines leaving the bottom and top platens, respectively (FIG. 4a). Further details of the flow pump operation are described in McCartney and Znidarčić (2010).

3.2 *Temperature Control System*

The temperature of the cell water and soil specimen is regulated using three 110 V, 400 W Watlow Firerod© Heating Cartridges with dimensions of 177.8 mm in length and 6.35 mm in diameter, fixed to the base of the triaxial cell.

The heating cartridges are controlled using a Watlow EZ-ZONE© PM temperature controller, which is connected to an Omega K-Type thermocouple (TC) probe located at the base of the cell. This system operates using a temperature feedback loop and is capable of maintaining temperatures at the location of the operating thermocouple to a tested accuracy ±0.05 °C. The temperature control system is capable of precisely ramping of temperature within the cell, allowing for the application of slow temperature rates. A second Omega K-Type TC probe is mounted to the top of the triaxial cell to monitor the development of thermal gradients within the cell chamber. To minimize the temperature gradient, a Topsflo TS5 15PV circulatory pump is used to circulate cell water in the cell. For a target temperature of 50 °C, this system was observed to reduce the temperature gradient within the cell from 2.0 to 0.1 °C. The circulation pump, which has a pressure limit of 700 kPa, can be detached using quick-connect fittings when applying high stresses to the specimen. Finally, the cell is wrapped in 6.35 mm-thick thermal insulation to minimize heat loss during testing.

3.3 *Mechanical Loading System*

Cell pressures are applied using a "high pressure" flow pump, similar to the pore water flow pump, with a piston cross-sectional area of 4793 mm^2. Movement of the piston during testing is controlled and monitored by a similar stepper motor to that used for the pore water pressure pump. The flow pump is designed to supply pressures to the triaxial cell up to 10 MPa. Internal cell pressures are maintained within the triaxial cell using a feedback control loop incorporating a 3500 kPa Geotac pressure sensor. When provided a target cell pressure, the system controller will move the cylindrical piston in or out of the stainless steel reservoir until the target pressure is met according to an accuracy value input into the program. During changes in soil specimen volume, due to either mechanical or thermal loading, the circular piston will move in order to maintain constant cell pressure. Movement of the piston will correspond to changes in the cell water volume and can be calibrated to accurately determine corresponding changes in volume of the soil specimen.

4 MACHINE DEFLECTION CALIBRATION

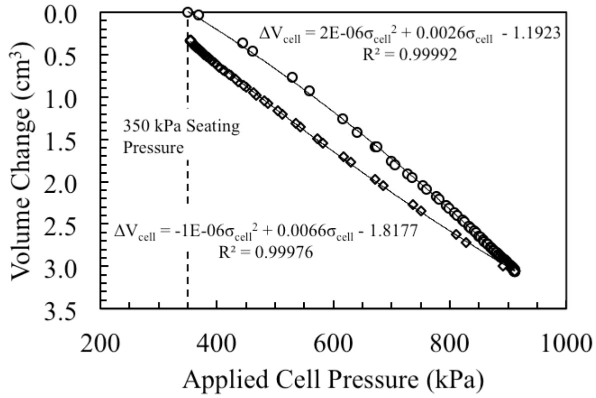
To determine the volume change of a soil specimen due to changes in stress and/or temperature using the flow pump, it is necessary to characterize the mechanical and thermal deformations of the thermal triaxial cell equipment under conditions similar to those during testing. The mechanical and thermal machine deflections of the new triaxial cell are determined by testing a 51.2 mm-tall, 63.3 mm-diameter aluminum "dummy" specimen with a known Young's Modulus of 68.9 GPa and a coefficient of volumetric thermal expansion of 69.0×10^{-6}/°C. For mechanical and thermal loading paths, the total volume change, as determined by the flow pump, is equal to the sum of the volume change of the triaxial cell and the dummy specimen:

$$\Delta V_T = \Delta V_{cell} + \Delta V_{dummy} \quad (3)$$

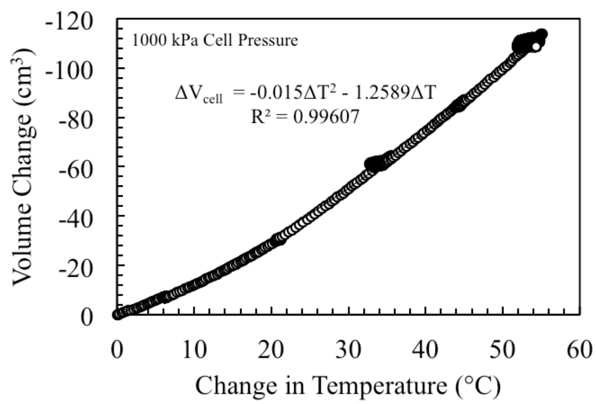
where ΔV_T, ΔV_{cell}, ΔV_{dummy} are the total volume change measured by the flow pump, triaxial equipment, and dummy specimen, respectively. Eq. 3 may be rearranged to determine the triaxial cell deformations for changes in stress or temperature:

$$\Delta V_{cell}(\Delta T,\Delta\sigma_{cell}) = \Delta V_T - \Delta V_{dummy} \quad (4)$$

The observed mechanical and thermal cell deformations are shown in Figures 5a and 5b, respectively. Positive values of volume change indicate volumetric contraction, and are measured by tracking the advancement of the piston of the high pressure flow pump into its reservoir.



(a)



(b)

Figure 5. Cell deformations: (a) Mechanical; (b) Thermal

The volume change of the triaxial equipment due to changes in cell pressure were determined by applying a loading/unloading cycle between 350 and 900 kPa to the dummy specimen at an initial cell pressure of 350 kPa (typically applied during backpressure saturation). During initial loading, a nonlinear, irrecoverable contraction was observed, followed by a linear-elastic response during unloading, shown in Figure 5(a). For reference, the dummy specimen is expected to compress by 1.52×10^{-3} cm^3 for an applied change in stress from 350 to 900 kPa. Thermal machine deformations of the cell were also evaluated by heating the "dummy" specimen from 24 to 80 °C at a cell pressure of 1000 kPa. A nonlinear relationship was observed between cell volume change and change in temperature as shown in Figure 5(b). The dummy specimen expands by 0.62 cm^3 for a change in temperature of 56 °C. The volume change of the soil during mechanical and thermal loading can be determined as follows:

$$\Delta V_{soil}(\Delta T, \Delta\sigma_{cell}) = \Delta V_T - \Delta V_{cell} \quad (5)$$

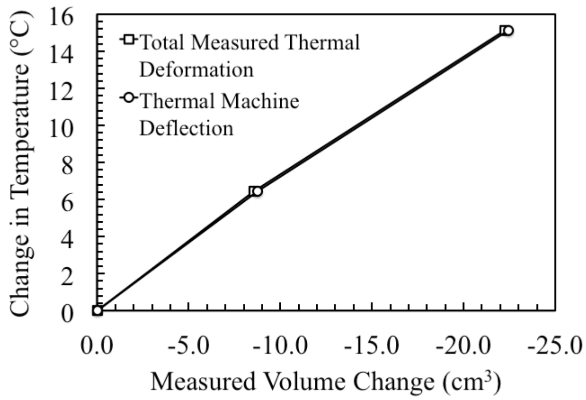
5 MATERIALS & PREPARATION

Compacted Bonny silt was selected for testing using the thermal triaxial cell. Bonny silt is an ML silt with liquid and plastic limits of 25 and 21, respectively, and a fines content of 83.9%. An activity of 0.29 indicates that Bonny silt does not contain a significant amount of active clay minerals.

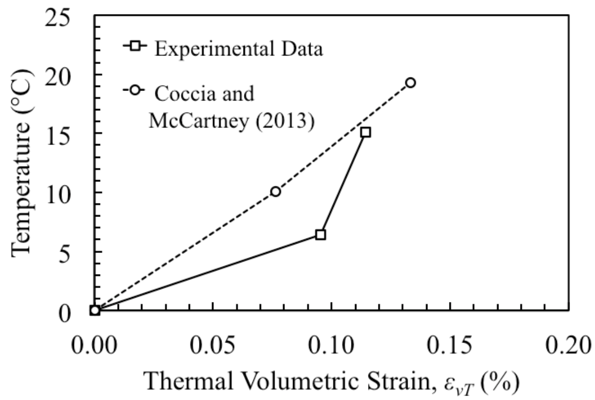
A 50.8 mm-tall, 63.5 mm-diameter test specimen was prepared in 2 equal lifts using static compaction within a cylindrical steel mold. The target gravimetric water content was 15.0%, which is 1.4% wet of optimum, and the target dry density was 1.7 g/cm^3. Each compacted lift was scarified to minimize potentially weak planes within the cylindrical specimen. After placement in the cell, a vacuum was applied to the specimen. The cell pressure was then increased to 50 kPa and a water pressure of 20 kPa was applied to the bottom of the soil specimen. This process continued until an equivalent of 2 pore volumes of water was flushed through the sample, taking an average of 24 hours. The top line was then flushed with de-aired water and a backpressure of 320 kPa was applied with a cell pressure of 350 kPa. The sample was considered saturated once a *B* value greater than 0.96 was measured.

6 EXPERIMENTAL EVALUATION

A suction-controlled drained heating test was performed on a specimen of unsaturated silt to present the thermal volume change measurement capabilities of the new triaxial system. Following backpressure saturation, the sample was brought to equilibrium under a target matric suction of 50 kPa, corresponding to a measured soil degree of saturation of 0.82. The volume of water expelled was continuously monitored until no change in pore water was observed for a period of 5 hours. The cell pressure was then increased to 1000 kPa to ensure normally consolidated conditions, and allowed to reach equilibrium. Once at steady state, the soil was heated to 30 °C at a rate of 2 °C/hr. The soil was maintained at 30 °C for a 12 hour period to ensure the complete dissipation of thermally generated excess pore water pressure. Following the first temperature increment, the soil was again heated from 30 to 40 °C. During heating, the volume change of the soil specimen and triaxial equipment were monitored using the high pressure flow pump and are presented for comparison in Figure 6(a). The recorded total volume change data was calibrated by substituting the relationship determined in Figure 5(b) into Eq. 5. The volumetric strain results are shown in Figure 6(b). The silt contracted by 0.11% for an increase in temperature of 15.1 °C. The results are in agreement with those measured for saturated Bonny silt by Coccia and McCartney (2013) in a true-triaxial cell.



(a)



(b)

Figure 6. Data for unsaturated Bonny silt at a suction of 50 kPa: (a) Total volume change versus expected thermal deformation and; (b) Thermal volumetric strain versus temperature

7 CONCLUSION

A new thermal triaxial cell is introduced which is capable of applying cell pressures up to 10 MPa. A procedure was developed to determine the thermal volume change behavior and impact of changes in temperature and matric suction on the effective preconsolidation stress of unsaturated soils subjected to low suction magnitudes. In addition to presenting the details of the new triaxial equipment, the thermal and mechanical machine deformations are characterized to accurately determine the volume changes of soil. The results from a drained heating test on normally consolidated unsaturated silt were found to be consistent with those from the literature for similar soil types and from different experimental setups.

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