Laboratory testing of unsaturated soils under simultaneous suction and temperature control

Test de laboratoire des sols non saturés avec contrôle simultané de la succion et de la température

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ABSTRACT: The paper presents recent developments in laboratory testing related with the thermo-hydro-mechanical characterization of soil properties. Main problems concerning axis translation technique application at high temperatures are described. Selected test results of non-isothermal paths at constant matric suction are presented for different artificially prepared clay fabrics.

RÉSUMÉ: L' article présente des développements récents concernant différentes techniques de laboratoire en relation avec la caractérisation thermo-hydro-mécanique du comportement des sols. Les problèmes principaux associés à l'application de la technique de la translation d'axe à hautes températures sont décrits. Des résultats d'essais sur des chemins non isothermes à suction constante obtenus sur des échantillons d'argile artificiellement préparée et de diverses textures sont présentés.

1 INTRODUCTION

The need to tackle some of the novel Geotechnical Engineering problems requires the extension of current understanding of soil behavior by incorporating relevant stress and environmental state variables. Two of such variables are discussed in the paper from an experimental point of view and regarding their effects on hydro-mechanical behavior of clays: suction (a stress state variable) and temperature (an environmental state variable).

Research carried out during the last decades has provided experimental evidence that matric suction plays an important role in unsaturated soils. On the other hand, in view of the increasing use of geomaterials in high-temperature environments, temperature effects in non-isothermal situations have received increasing attention. Engineered barriers for the storage of high-level radioactive wastes in deep geological formations is an example of a geotechnical engineering problem in which both partial saturation and temperature are important factors of behavior. Therefore, it is necessary to extend current equipment and experimental techniques to investigate unsaturated states under non-isothermal conditions and to provide reliable descriptions of the stress-strain behavior of soils.

There are a number of laboratory results concerning thermal effects on saturated soils and recent works on this area are described in Delage et al. (2000) and Burghignoli et al. (2000). However, the experimental incorporation of temperature in partially saturated soils has not been so well studied, mainly due to the difficulty of controlling water phase changes in an open thermodynamic system. This limitation makes impossible the application of back pressures with the purpose of avoiding water phase changes at high temperatures. Saix & Jouanna (1990) and Saix (1991) reported the first experimental results at relatively low matric suction values (suction values lower than 5 kPa). Recordon (1993) and Wiebe et al. (1998) have studied the consequences of thermal loading in partially saturated soils at constant water content and without suction control (closed system to vapor). Romero et al. (1998) and Romero (1999) presented results of thermal loading with suction control using axis translation technique (open system to vapor).

2 LABORATORY TESTING

2.1 *Equipment*

Equipment in which temperature and suction can be simultaneously and independently controlled is relevant to the thermo-hydro-mechanical characterization of soil properties. Two of such apparatuses have been developed and carefully calibrated: a temperature and suction controlled oedometer cell (Romero et al. 1995) and a triaxial equipment (Romero et al. 1997, Romero 1999).

Figure 1 shows the layout of an oedometer cell and a number of auxiliary devices necessary to perform the tests. Soil temperature, ranging from ambient to 80°C, is measured by thermocouples located close to the sample, which are used as feedback signals acting on a programmable thermostat. This equipment controls a heater submerged in a silicone oil bath (1 in Figure 1). Temperature rise to the target value can be electrically regulated during the heating path, a minimum rate being 5°C/hour.

A water volume change indicator connected to a high air-entry value (HAEV) ceramic disc (3 in Figure 1) and maintained at a reference laboratory temperature is used to obtain values of inflow/outflow and water retention for each suction and temperature condition. Matric suction is controlled by air overpressure technique in which an elevated air pressure is applied to the specimen (4 in Figure 1). This method translates water pressure in the positive range, the same as axis translation technique, but regulates matric suction under constant air pressure and variable water pressures. The term matric suction refers to the control of the water potential by means of an experimental technique in which water transfer is primarily carried out in liquid phase through a ceramic disc permeable to solutes.

2.2 *Problems with air overpressure technique application*

Main problems concerning air overpressure technique application at high temperatures are associated with the accumulation of dissolved air beneath the HAEV ceramic, the control of the relative humidity in the air pressure system and the progressive clogging of the ceramic disc due to cation exchange effects through water. Only the first two phenomena are discussed in this section.

With regard to the first phenomenon, it can induce the progressive loss of continuity between the pore water and the water in the measuring system. This dramatic slowing of the liquid phase transfer can induce shrinkage due to soil water evaporation, which can be confused with the same volume change response associated with thermal contraction. Therefore, an auxiliary equipment (diffused air flushing system indicated in Figure 1) is required to flush and measure periodically air bubbles passing in solution through the HAEV ceramic. An increase of

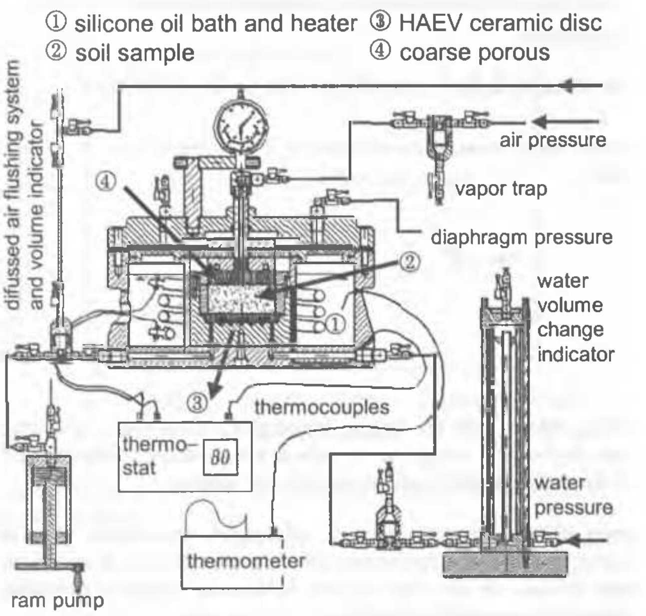

Figure 1. Experimental set-up for suction and temperature controlled tests (Romero et al. 1995).

the air diffusion coefficient through saturated ceramic discs upon heating has been measured by Romero (1999): between 6×10^{-11} and 1×10^{-10} m^2/s at 22°C and between 2×10^{-10} and 3×10^{-10} m^2/s at 80°C (disc porosity $n = 0.31$). In addition, an increase of the volumetric coefficient of solubility of air in water is observed at higher temperatures. This way, an alternative is to use nitrogen for applying air overpressure due to its lower volumetric coefficient of solubility in water compared to air.

Concerning the second phenomenon of vapor transfer between the soil and the open system of the air pressure line, it can be controlled with a vapor trap that maintains a high relative humidity in the air chamber (refer to Figure 1). Evaporative fluxes are originated due to the difference in vapor pressure between soil voids and this air chamber. Volumetric fluxes can be detected in the water volume change indicator under steady state conditions.

A series of 1-D coupled thermo-hydraulic analysis were carried out by Romero (1999) to simulate evaporative fluxes and matric suction evolution during a wetting path at high temperatures (80°C). The analysis performed took into account the following coupled phenomena: heat transport (heat conduction, heat convection and phase changes) and water flow (liquid phase by Darcy's law and vapor diffusion according to Fick's law). The simulation of these interacting phenomena was achieved via a finite element code (Code-Bright: Olivella et al. 1996). Hydraulic properties of the clay were selected according to test results reported by Romero (1999). Figure 2 to shows the time evolution of matric suction during a wetting path for three representative points, starting from an initial value of $s_o = 1.6$ MPa to a target $s_f = 0.45$ MPa that is applied with air overpressure technique. An initial relative humidity of the air chamber of $h_{ro} = 50\%$ was assumed in accordance to the relative humidity of the laboratory. Different final relative humidity values were prescribed at the top surface of the sample in contact with the air chamber (refer to the scheme shown in Figure 2): $h_{rf} = 80\%$, 90%, 95% and 99.7% (simulation of a closed system to vapor). The main goal of the simulations was to determine the feasibility of the applied matric suction to be equalized throughout the sample height of 10 mm (soil in contact with ceramic, mid-height and soil in contact with coarse porous stone, as indicated in Figure 2). Two different water fluxes are involved in the process (refer to the scheme shown in Figure 2). Firstly, an evaporative flux that tries to dry the clay dependent on both soil properties (mainly vapor diffusivity) and boundary conditions (relative humidity of air chamber above the evaporating surface). Secondly, a liquid water flux through the HAEV ceramic disc that is dependent on soil and ceramic disc permeability. Calculated values of volumetric evaporative fluxes, E_v, are also represented in the figure.

According to Figure 2, water evaporation will cause an initial drying of the clay upper surface. This drying is progressively slowed and reverted as a higher relative humidity of the air chamber is attained. On the other hand, a monotonic suction reduction is detected at the bottom boundary of the sample. As observed in this figure, at the end of the wetting path and under steady-state conditions, full matric suction equalization has not been achieved in the open system to vapor. Matric suction equalization is approximately ensured when a relative humidity over 95% is maintained in the air chamber. This is equivalent to accept volumetric evaporative fluxes $E_v < 2.9\times10^{-6}$ $(mm^3/s)/mm^2$. Romero (1999) recommended a relative humidity higher than 98.5% (or $E_v < 1\times10^{-6}$ $(mm^3/s)/mm^2$) to limit vapor transfer at high temperatures (up to a maximum of 80°C) and to attain matric suction equalization over the entire sample height.

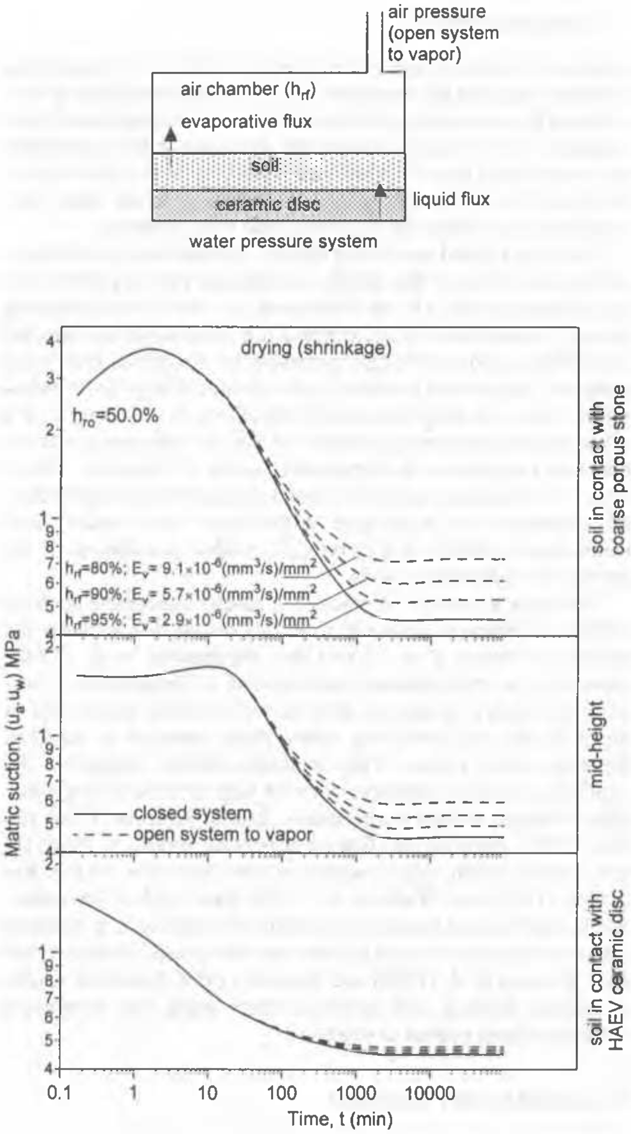

Figure 2. Numerical results of matric suction evolution during a wetting path (initial suction: $s_0 = 1.6$ MPa; target suction: $s_f = 0.45$ MPa).

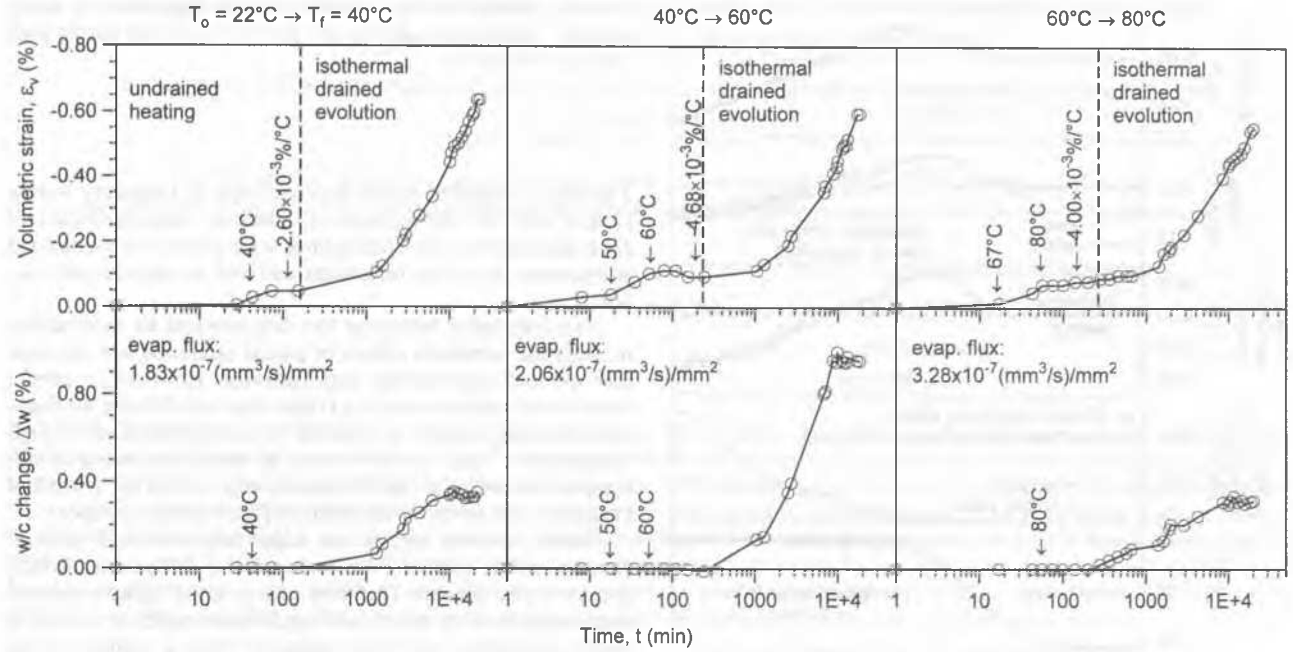

Figure 3. Time evolution of volumetric strain and water content change during a drained heating path at constant matric suction.

3 NON-ISOTHERMAL RESULTS

3.1 *Test results on a heavily overconsolidated sample*

Two types of tests can be performed concerning temperature control: isothermal paths at high temperatures and non-isothermal (heating or cooling) paths. This section focuses on non-isothermal paths. With regard to these paths, they can also be classified in undrained and drained heating paths. In the last type of tests, heating or cooling rate is applied slowly enough to ensure no significant increase or decrease of interstitial fluid pressures (temperature rates of 0.1°C/hour to 0.8°C/hour for a clayey soil presenting a drainage distance of 40 mm). However, an alternative is to apply temperature changes at higher rates (around 5°C/hour) and then allow to equalize at constant temperature until pore pressure equalization is reached (Romero 1999). In processing non-isothermal results, careful cyclic calibrations should be carried out in order to account for water volume change of the transmission lines and thermal dilatation of the different cell components.

Figure 3 presents non-isothermal evolutions under oedometer conditions carried out on a heavily overconsolidated clayey sample, which was brought to the desired matric suction in a wetting path and then subjected to heating (up to 80°C) under constant net vertical stress, $(\sigma_v\text{-}u_a)$ = 0.03 MPa, and matric suction, s = 0.06 MPa. Dilative strains are considered negative and a positive water content change denotes water inlet. The samples were prepared by one-dimension static compaction at a constant water content of w = 15%. The initial conditions of the sample are e_o = 0.763 and w_o = 25.4%. The drainage lines were kept open throughout the paths and temperature was raised in steps at a rate of 5°C/hour. Every 20°C the temperature increase was stopped to allow for pore pressure equalization. The sample initially expands in the quasi-undrained phase with no significant water content change (w/c plot in Figure 3). Thermal volume expansion coefficients under quasi-undrained conditions are also indicated in the figure. An isothermal drained evolution follows, in which a swelling tendency with water absorption is observed during pore pressure equalization. Drained thermal equalization phase is interrupted after 2 weeks, corresponding to a relatively stable water content change. Evaporative fluxes, which increase with increasing temperature as indicated in Figure 3, have been maintained under the limit value indicated in the previous section.

Figure 4 shows heating-cooling results performed at constant net vertical stress, $(\sigma_v\text{-}u_a)$ = 0.03 MPa, and at two different matric suctions (s = 0.06 MPa and 0.20 MPa). Tests were performed under oedometer conditions on the heavily overconsolidated clayey sample previously described. It is important to indicate that these results are possibly affected by certain loss of K_0 condition caused by ring expansion and contraction. Nevertheless, it is assumed that these consequences do not present an important influence on the volume change behavior of the overconsolidated fabric with high swelling capacity (Romero et al. 1998). Marked stress-path dependencies are observed in Figure 4, where reversible and irreversible components of volumetric strains are identified. In addition, some dilative strain accumulation is detected in the subsequent cooling-heating path.

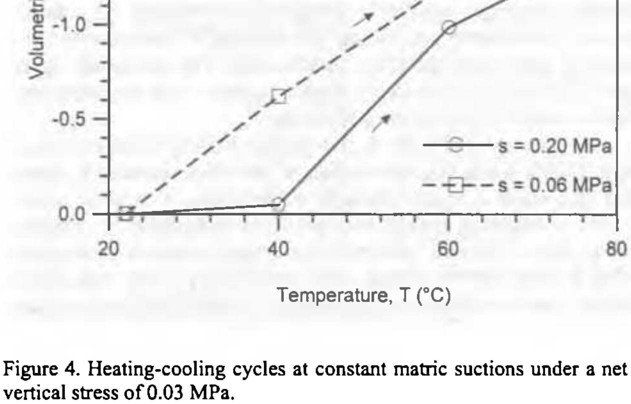

Figure 4. Heating-cooling cycles at constant matric suctions under a net vertical stress of 0.03 MPa.

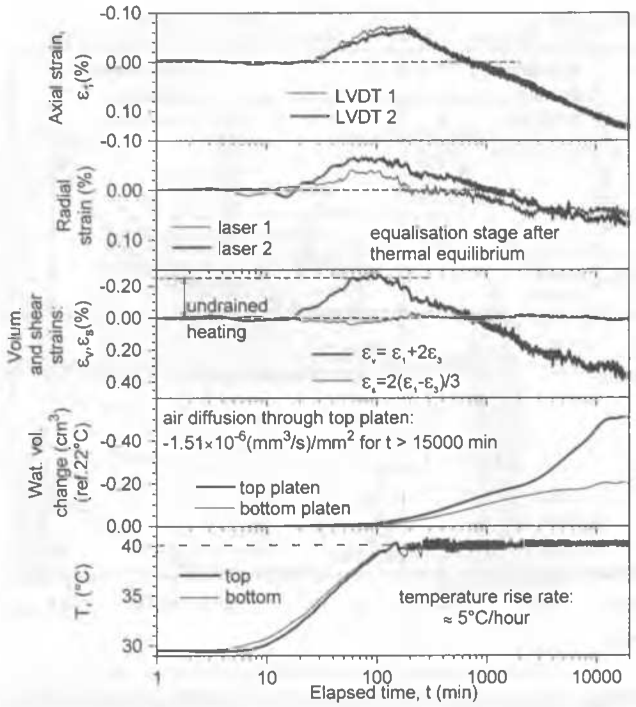

Figure 5. Time evolution of strains and water volume change during heating and regulation phase at constant s= 0.20 MPa.

3.2 *Test results on a normally consolidated sample*

Non-isothermal paths at constant matric suction, $s = 0.20$ MPa, and under constant net mean stress, $(\sigma_m - u_a) = 1.0$ MPa, were performed on a normally consolidated clay. Testing program was carried out under isotropic stress state using a suction (via overpressure technique) and temperature controlled (via silicone oil forced convection system) triaxial cell, which is described by Romero et al. (1997) and Romero (1999). This fully instrumented equipment allows registering the time evolution of axial (via internal LVDTs) and radial deformations (via electro-optical laser sensors) that experiences the sample.

Figure 5 shows the time evolution of strains (axial, radial, volumetric and shear) and water volume changes (reference temperature 22°C) during a heating path starting from 30°C to 40°C at a rate of 5°C/hour. After this temperature rise, the sample was allowed to equalize the excess pore pressures generated by this quasi-undrained heating phase. This way, experiments are initially not true drained tests with restricted drainage due to soil permeability and ceramic disc impedance effects. During this quasi-undrained stage, matric suction diminishes due to water pressure build-up. It is assumed that this analogous to wetting stage takes place under reversible conditions without any appreciable yielding. The increase of pore water pressure with no change in boundary confining stress was analyzed by Romero (1999) assuming volumetric compatibility between soil matrix and its constituents and taking into account of both thermal expansion and compressibility coefficients. The estimated water pressure build-up stays below matric suction value in such a way that no water overpressure is generated.

As observed in Figure 5, the sample initially dilates with no appreciable water volume change in the quasi-undrained phase, but afterwards a nearly isotropic compression with some water outlet is observed during pore pressure dissipation at constant temperature. Drained thermal equalization phase is interrupted after 2 weeks testing period, when a relatively stable volumetric steady state is achieved (a volumetric strain rate of less than 0.01%/day). The isotropic rise in axial and radial strains produced under quasi-undrained conditions is mainly originated due to water thermal expansion. Afterwards, due to the loss of shearing strength of the contacts between aggregates, a nearly isotropic compression of the soil skeleton develops during pore pressure dissipation.

4 CONCLUSIONS

The paper presented recent developments in laboratory testing related with the thermo-hydro-mechanical characterization of geomaterial properties. Descriptions were given for a suction and temperature controlled oedometer cell and its experimental layout.

Axis translation technique has demonstrated its applicability to study the combined effects of partial saturation and temperature on hydro-mechanical soil behavior. However, a careful control with auxiliary devices (vapor trap and diffused air flushing/measuring system) is required to use this technique at high temperatures. Main problems refer to the accumulation of diffused air beneath the HAEV ceramic disc and to the control of evaporative fluxes in the air chamber (open system to vapor).

Finally, selected test results under non-isothermal paths at constant matric suction were presented for different artificially prepared clay fabrics. Transient phases (both quasi-undrained and drained heating stages) and equilibrated states at the end of every temperature step were presented from a heating-cooling test program carried out on heavily overconsolidated and normally consolidated samples.

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