Some Aspects of the Effect of the Temperature on the Behaviour of Unsaturated Sandy Clay

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Summary. The paper describes experimental results on triaxial paths at high temperature concerning an unsaturated clay ($w_L = 38\%$, $I_P = 19$ and $C_c = 0.23$). Unsaturated drained triaxial compression tests on normally consolidated samples were carried out at constant temperatures varying from 22 to 80°C. Desaturation of samples were carried out by the imposition of suctions using the osmotic method. This required the development of a new triaxial cell equipped with a collar heating and an osmotic pedestal which allows the circulation of an osmotic solution of Poly Ethylen Glycol (PEG) 6000, in contact with the sample via a dialysis membrane. The principal phenomena simultaneously related on the temperature and saturation were highlighted, in particular the hardening of material on isotropic path, a secant modulus which decreases with temperature and increases with suction, a light reduction in the maximum stress on deviator path at high temperature and the increase in this maximum stress when suction increases.

Key words: unsaturated triaxial path, normally consolidated, temperature, suction, THM behaviour, osmotic method

1 Introduction

The study of the thermo-hydro-mechanical behaviour of saturated and unsaturated soils is a very complex problem, and it is often useful to uncouple the effects of temperature, mechanical loading and negative pore water pressure or suction. This problem was tackled by several authors, either by comparing the soil mechanical behaviour at various temperatures under isothermal conditions, or by varying the temperature under constant stress. The main conclusions of these studies are as follows:

- On normally consolidated path, an increase in temperature results in a densification of the soil. On oedometric and isotropic normally consolidated paths, the temperature causes a reduction in the void ratio (Fleureau and Kheirbek-Saoud 1992, Rahbaoui 1996) whereas, on an overconsolidated path, the temperature causes a dilation Belanteur et al. (1997), Sultan et al. (2002).

- In the case of overconsolidated soils, one observes that an increase in the temperature erases the overconsolidation of the material (Rahbaoui 1996).
- An increase in temperature reduces the mechanical strength of soils (Sultan et al. 2002, De Bruyn 1999, Belanteur et al. 1997). Other authors show an increase in the mechanical strength with temperature (Tanaka et al. 1997). In this case, a detailed attention must be given to the type of studied material, its initial state and its mode of preparation to clarify these contradictions.
- A few authors show that temperature reduces the value of the slope M in the plan $[p'; q]$ plane (De Bruyn 1999). However, others show little or no influence of the temperature on the value of M, and sometimes a slight increase of this parameter (Tanaka et al. 1997).

Concerning the THM behaviour of the unsaturated soils, very few results exist in the literature. This is due to the complexity of the experiments, their duration and the number of parameters to be controlled (El Youssoufi et al. 2002). Recent works show on the one hand, a reduction in suction when the temperature increases for a given water content (Romero 1999) and, on the other hand, an increase in strength with temperature for a given suction (Jamin 2003).

This paper presents experimental results allowing the study of the effect of the temperature on the behaviour of unsaturated clay on triaxial paths.

2 Materials and Experimental Devices

The material used is a mixture made up of kaolinite (90%), Hostun RF sand (5%) and silica (5%). The percentages were elaborate after several granulometry curves on various proportions. This combination has a continuous granulometry curve. This mixture will be called "sandy clay." The principal characteristics are given in Table 1.

The study of unsaturated triaxial paths according to the temperature required the development of a triaxial cell of 3.5 MPa of confining pressure (Fig. 1). The heating system is composed of a heating insulated collar with an internal diameter of 146 mm and a 230 mm height, developing a power of

Table 1. Description of the material used

Material	w_L (%)	I_P (%)	% < 80 µm	% < 2 µm	d_{10} µm	d_{60}/d_{10}
Sandy Clay	38	19	95	53	0.2	21

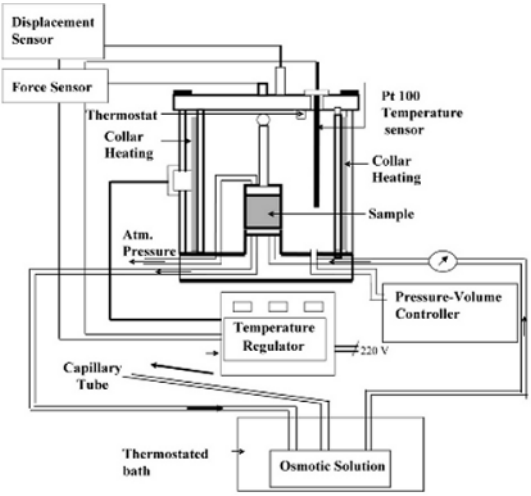

Fig. 1. Unsaturated triaxial cell with controlled temperature and imposed negative pore water pressure by the osmotic technique

1800 W. This collar comes to wrap an aluminum hollow roll. The imposition of a given temperature to the sample is controlled by an electronic regulator of temperature and a Pt100 probe. A thermocouple is used to measure the imposed temperature. Regulation and measuring equipment was developed. Like system of safety, thermostats were fixed in various places of the cell. To impose or control pressures and volumes, three pressure-volume controllers were used. The axial loading is carried out using a 25 kN loading frame. This instrumentation is controlled via a HP station.

In addition, a special pedestal at the bottom of the sample was developed to make it possible to impose negative pore water pressures using the circulation of a PEG solution in contact with the sample via a dialysis membrane. A brass plate, 2.5 mm in thickness and 35 mm in diameter, perforated by holes of 1.5 mm in diameter, comes to cap the cell pedestal. This plate serves as basis for the sample. Between the perforated plate and the sample, a disc of dialysis membrane is placed over the perforated plate. In order to prolong the lifespan of the dialysis membrane and to avoid its degradation by the bacteria naturally present in the soil, a small quantity of benzoic acid, acting like an anti-bacterial, was added to the PEG solution. In addition, the imposition of a negative pore water pressure in the soil sample using the osmotic technique is based on the assumption that the air pressure within the sample is equal to the atmospheric pressure. This condition is ensured by putting the draining circuit at the top of the sample to the atmospheric pressure. To maintain a constant concentration of the osmotic solution in the circuit, a circulation between the chamber of the pedestal and an external tank is carried out by means of a peristaltic pump of low flow.

3 Results and discussion

3.1 Effect of Temperature on Pre-Consolidation Stress in Isotropic Paths

To study the effect of temperature on the preconsolidation pressure, several tests were carried out at four values of temperature (22, 40, 60 and 80°C). Samples were first preconsolidated at isotropic effective stress $p' = 200\,\text{kPa}$, then heated at different temperatures. At equilibrium, isotropic effective stress was increased with a constant temperature. The preconsolidation stress p'_c is evaluated as the stress value at the intersection of the two linear parts of the compression curves (logarithm of mean effective stress versus void ratio). One observes a quasi linear decrease of the preconsolidation pressure when the temperature increases (Fig. 2). This is in agreement with the results from the literature (Sultan et al. 2002, Cekerevac and Laloui 2004). Cekerevac and Laloui (2004) suggested a semi-logarithmic expression to describe this decrease

$$\sigma'_c(T) = \sigma'_c(T_o)\{1 - \gamma \log[T/T_o]\}\,. \tag{1}$$

3.2 Effect of Temperature on Secant Modulus

E_{50} Secant modulus is defined as

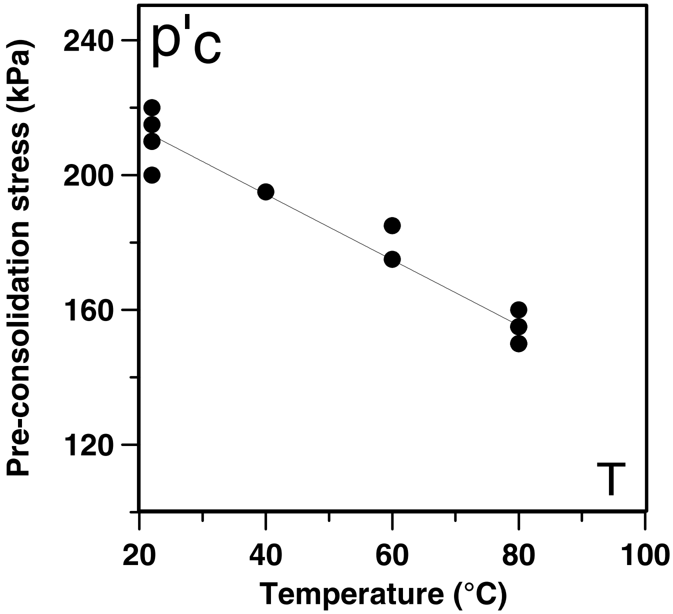

Fig. 2. Influence of temperature on preconsolidation pressure

$$E_{50\%} = \frac{q_{\max}/2}{\varepsilon_{50\%}}\,. \tag{2}$$

where, $q_{\max}$ is the maximum deviatoric strength and $\varepsilon_{50\%}$ is the axial strain corresponding to 50% of maximum deviatoric strength.

Deviatoric loading tests on triaxial paths were carried out at three values of temperatures (22, 60 and 80°C). Figure 3 shows the variation of secant modulus versus effective confining stress. One observes that for a given temperature, the secant modulus increases with effective confining stress. For a given effective confining stress, the secant modulus decreases when the temperature increases. The variation of secant modulus versus confining stress follows Hertz's law $E = \alpha(\sigma'_3)^n$ (Biarez and Taibi 1997), parameterized in temperature. Table 2 summarizes the parameters α and n according to the studied temperatures.

For unsaturated tests, several deviatoric loading tests were carried out on unsaturated samples at both constant suction and temperature. Figure 4 shows the variation of secant modulus versus suction for two values of temperature (22 and 80°C). The total confining stress was maintained equal to 1250 kPa. It is noted that the secant modulus increases with suction following a bi-logarithmic law $E = \beta(u_w)^m$ (Fleureau and Kheirbek-Saoud 1992). In addition, for a given suction, secant moduli at $T = 80°\mathrm{C}$ are lower than those

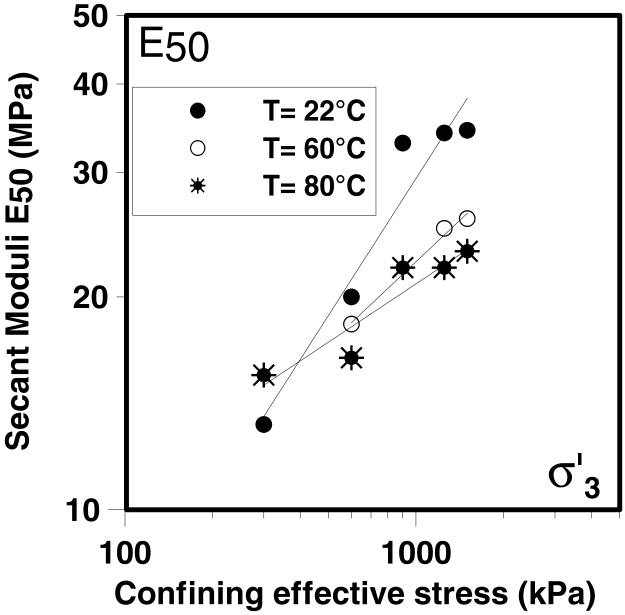

Fig. 3. Variation of secant modulus versus effective confining stress for three temperature

Table 2. Parameters α and n according to the studied temperatures

Temperature (°C)	n	α
22	0.64	0.086
60	0.39	2.63
80	0.27	14

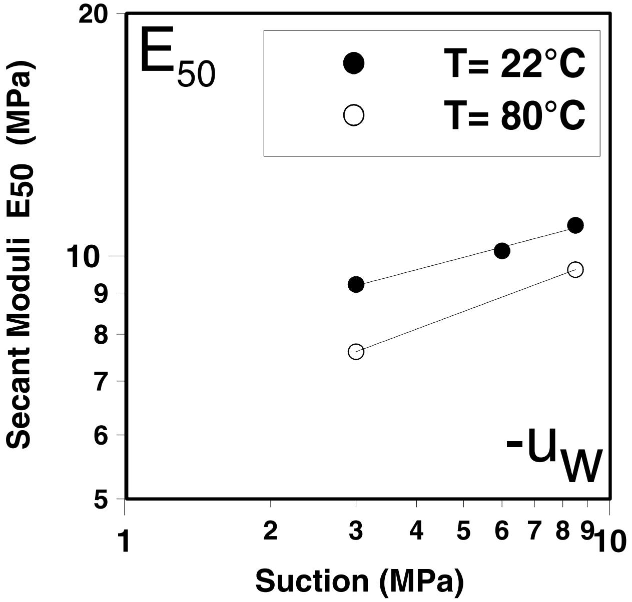

Fig. 4. Variation of secant modulus versus suction for two values of temperature (22 and 80°C)

corresponding to $T = 22°\mathrm{C}$. In all the cases, one notes a loss of rigidity when the temperature increases.

3.3 Effect of Temperature on the Shear Strength

Figure 5 shows an example of results of unsaturated triaxial compression tests on a normally consolidated sandy clay for two imposed suctions $s = -u_w$ (3 and 8.5 MPa) and two temperatures (22 and 80°C) in $[p + s, q]$ plan. It is noticed that the envelope of maximum strengths decreases when the temperature increases and for a given temperature, maximum strength increases with suction (Wiebe et al. 1998, Ghembaza 2004).

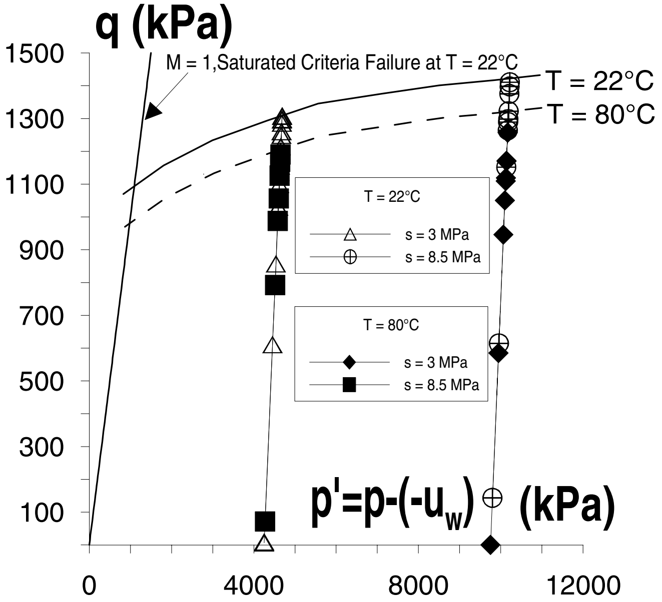

Fig. 5. Unsaturated triaxial compression tests on a normally consolidated sandy clay for two imposed suctions (3 and 8.5 MPa) and two temperatures (22 and 80°C) in $[p + s, q]$ plan

4 Conclusion

The results of laboratory study using a temperature controlled triaxial cell have been presented. Thermal effects on the mechanical behaviour of unsaturated sandy clay were analyzed by comparing tests at various temperatures and suctions. In the case of saturated soils, the preconsolidation pressure decrease when the temperature increases. This observation is in agreement with the results from the literature. It is about a negative hardening. In the case of unsaturated soils, the preconsolidation pressure increases with suction for a given temperature. It is about a hydrous hardening. For a null suction, the secant modulus follow a Hertz law $E = \alpha(\sigma'3)n$ with n decreasing when the temperature increases. For a non-null suction, the secant modulus increases with suction. For a given suction, this modulus decreases when temperature increases. In the case of unsaturated soils, the maximum strength decreases when the temperature increases, in spite of the hardening produced by the negative pressure. This strength increases with the suction, at a given temperature.

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