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On the thermal failure of sand-clay mixture

Sur la rupture thermique du mélange sable-argile

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ABSTRACT: Failure conditions in soils at elevated temperatures appear to be highly dependent on stress and temperature history. Temperature-controlled triaxial tests were conducted to gain a deeper understanding of the effects of stress and temperature history on the undrained strength of sand-clay mixtures. Particular attention was paid to the thermal behaviour of the sand-bentonite material considerining the thermal curing time effects. A comprehensive experimental programme was conducted consisting of (i) isotropic drained heating followed by undrained triaxial compression at room temperature and elevated temperatures and (ii) an isotropic drained heating and cooling cycle followed by undrained triaxial compression. The results provide insights into a wide range of thermomechanical behaviours in clays. Data obtained at elevated temperatures were compared with those obtained from tests conducted at ambient temperatures. Based on these comparisons, the study presents and discusses the thermal effects on various behaviours. These include the influence of thermal history on shear strength, experimental evidence of the influence of temperature on pore pressure and the thermal effects on elastic modulus. In addition, the evolution of negative excess pore water pressure as a function of temperature is discussed.

RÉSUMÉ: Les conditions de défaillance des sols à des températures élevées semblent dépendre fortement de l'historique de contrainte et de température. Des tests triaxiaux à température contrôlée ont été effectués pour acquérir une compréhension plus approfondie des effets du stress et de l'historique de la température sur la résistance non drainée des mélanges de sable. Une attention particulière a été accordée au comportement thermique dépendant du temps du matériau de sable-bentonite. Un programme expérimental complet a été réalisé composé de (i) un chauffage drainé isotrope suivi d'une compression triaxiale non draine à la température ambiante et des températures élevées et (ii) un cycle de chauffage et de refroidissement drainé isotrope suivi par une compression triaxiale non draineuse. Les résultats fournissent un aperçu d'un large éventail de comportements thermomécaniques dans les argiles. Les données obtenues à des températures élevées ont été comparées à celles obtenues à partir de tests effectués à des températures ambiantes. Sur la base de ces comparaisons, l'étude présente et discute des effets thermiques sur divers comportements. Il s'agit notamment de l'influence de l'histoire thermique sur la résistance au cisaillement, des preuves expérimentales de l'influence de la température sur la pression des pores et des effets thermiques sur le module élastique. De plus, l'évolution de la pression négative de l'eau des pores en excès en fonction de la température est discutée.

Keywords: Temperature; sand-bentonite material; thermal history; triaxial tests; shear strength.

1 INTRODUCTION

A realistic and robust analysis of thermo-hydro-mechanical (THM) coupling phenomena relevant to sustainable subsurface activities, such as geothermal energy production, temporary or seasonal storage of hydrogen fuel, long-term storage of CO2 and radioactive waste, and natural risk analyses, needs to be generalized to include the response of soil to heating and the effect of temperature on soil mechanical properties. Heating can cause alterations in the mechanical characteristics of geomaterials due to various physical processes at the microstructural level. Several such processes and alterations have been reported in laboratory experiments and are believed to be crucial for analyzing these geo-systems (see, for example, Hueckel and Baldi 1990; Delage et al. 2000; Cekerevac and Laloui 2004). It should be noted that there is not sufficient experimental data on the temperature dependency of shear strength due to the insufficient attention to thermal curing and the applied temperature history before failure. The volumetric behaviour due to temperature changes strongly depended on the stress history or the overconsolidation ratio (OCR). The peculiarities of the mechanical response of soil to heating established in early experiments consist of a substantial thermoplastic contraction at high external effective stress or low OCR (close to normally consolidated conditions), initial expansion followed by thermal contraction in slightly overconsolidated conditions, and thermal expansion at low external stress or high OCR, as well as the possibility of thermal failure during undrained heating under constant non-isotropic stress. Thermal failure refers to various soil failure conditions caused by elevated temperatures (Hueckel et al., 2009).

This contribution presents the principal results of an experimental investigation performed on saturated sand-clay mixtures to investigate the role of the thermomechanical loading history prior to undrained triaxial loading. Isotropic drained heating followed by undrained triaxial compression tests was performed at elevated temperatures to evaluate the role of thermal and mechanical soil history in reaching failure. Therefore, a new thermal triaxial device was developed for this purpose. The results were compared with the mechanical responses of the samples at the reference (ambient) temperature. The testing tools used, the experimental procedure employed, and the material studied are first described, and the results of the experimental campaign are presented and discussed afterwards.

2 MATERIALS AND METHODS

Clay and silica sand were mixed and compacted in eight equal layers in a cylindrical mould. The physical properties of these soils are presented in Table 1 (more details can be found in Shirasb et al. 2020). Undrained triaxial tests were carried out using a modified thermal triaxial cell with an electronic data logger system capable of measuring axial stress, axial strain, volume change, and excess pore water pressure. The triaxial cell was calibrated to handle pressures up to 2000 kPa and temperatures up to 90°C. Heating was induced by placing a spiral heater around the specimen. After preparing the samples, a back pressure of 700 kPa was applied until a Skempton B value of 0.95 during six days of saturation. The time required to complete the thermal consolidation tests was less than 40 h at all temperatures and confining pressures.

The thermal and mechanical histories of the soil appear to be crucial to understanding how the failure condition varies with temperature. Two cases with different stress histories were considered, as discussed below.

Case 1: Isotropic drained heating followed by undrained triaxial compression at elevated temperatures.

Case 2: Isotropic drained heating and cooling cycles, followed by undrained triaxial compression.

In the first set, sand-clay samples were consolidated for five days at constant temperatures of $20^{\circ}\mathrm{C}-40^{\circ}\mathrm{C}-60^{\circ}\mathrm{C}$ and $80^{\circ}\mathrm{C}$ under confining stresses of 100 kPa $-$ 500 kPa and 1000 kPa. After consolidation, the undrained shear load started at a rate of 0.2 mm/min. The loading continued up to the axial strain of about 20%. During shear loading, deviatoric stress, axial strain, and excess pore water pressure were measured using calibrated sensors and a data acquisition system. Thermal stress paths were applied to the samples in the second group of tests, and their behaviour was monitored. Two samples were heated from the reference temperature 20°C to 80°C under the confining pressure of 100 kPa for five days and 1 day. Subsequently, the temperature decreased to the reference value and sheared after thermal equilibrium in an undrained condition.

Table 1. Physical properties of the tested soils.

Property	Sand	clay	1: 1 mixture
Name (**USCS***)	SW	CH	CH
Clay (%)	0	68	34
Silt (%)	2	31	16.5
Sand 0.06-0.2 (mm)	23	1	12
Sand 0.2-1 (mm)	55	0	27.5
Sand (>1 mm)	20	0	10
LL (%)	−	179	83
PI (%)	NP	125	57
w_{opt} (%)	−	−	21.4
$\gamma_{d,\max}$ (kN/m^3)	−	−	17.0

3 RESULTS AND DISCUSSION

For case 1, the samples consolidated at the reference temperature showed smaller shear strengths than those consolidated at higher temperatures, as shown in Figure 1a, 1c, and 1e. The behaviour trend for these samples was consistent with the thermal behaviour of the normally consolidated clays reported in other studies (Kuntiwattanakul *et al.* 1995; Tanaka *et al.* 1997; Abuel-Naga *et al.* 2006). The shear strength of the thermally consolidated samples was also increased with increasing the confining pressures, as shown in Figure 1c and 1e. Also, based on the results of the first Case, the samples consolidated at the reference temperature showed positive pore water pressure, whereas the thermally consolidated samples exhibited a different trend of behaviour (Figure 1b, 1d, and 1f).

The induced pore pressure in these samples decreased with increasing temperature. The pore pressure reached negative values for the samples consolidated at higher temperatures. For example, the samples consolidated at 80°C experienced negative pore pressure at all confining pressures; however, at the temperature of 60°C negative pore pressure was only observed in the tests with confining pressures of 100 kPa.

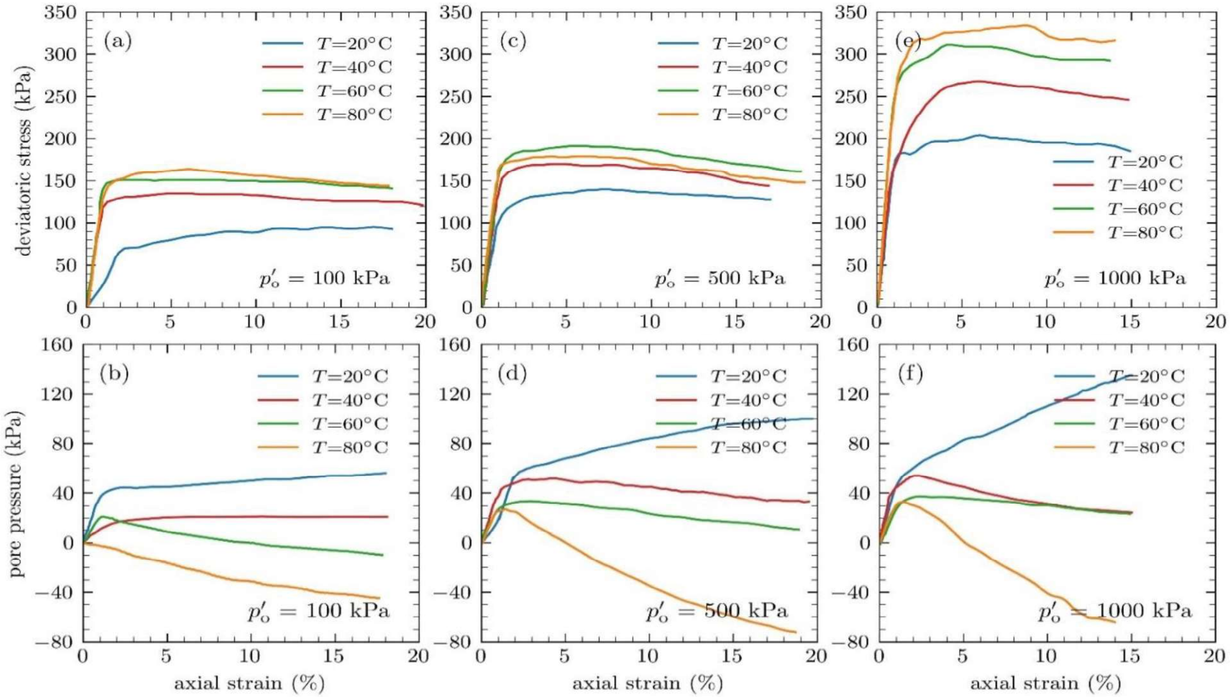

Figure 1. Results of undrained shear test on sand-clay mixture (Case 1).

The samples consolidated at 40°C did not show negative pore pressures for all confining pressures. The trend of excess variations in the pressure of the pore water at higher temperatures is similar to that of structured clays (Rios *et al.* 2014).

In Case 2, the shear strength and Skempton A coeffient were evaluated, the variation in shear strength with temperature is shown in Figure 2a, where the increase in peak shear strength during the thermal cycle is clearly identified. The sample with five days of thermal loading reached greater shear strength than the sample with one day of thermal loading. In case the samples are cooled again to reference temperature, the shear strength of the sample on day 5 of thermal loading is about 62% higher than the initial strength; however, the shear strength for the sample with one day of thermal loading increased by approximately 43%. Thermal consolidated samples also failed at the lower strain level and experienced softening behaviour, as shown in Figures 1c and 1e. The behaviour trend for the thermally cured samples was very similar to those for the structured or overconsolidated clays (Marques 1996).

Figure 2b shows the variations of Skempton's pore pressure coefficient, A (associated with the peak shear strength), with the temperature at the confining stress of 100 kPa. When the value of A is about 0.6 for the sample sheared at the reference temperature of 20°C, decreased to about zero for the sample consolidated for one day at 80°C and then was cooled to 20°C, or even to a negative value for the sample that was consolidated for five days at 80°C and was cooled back to the reference temperature.

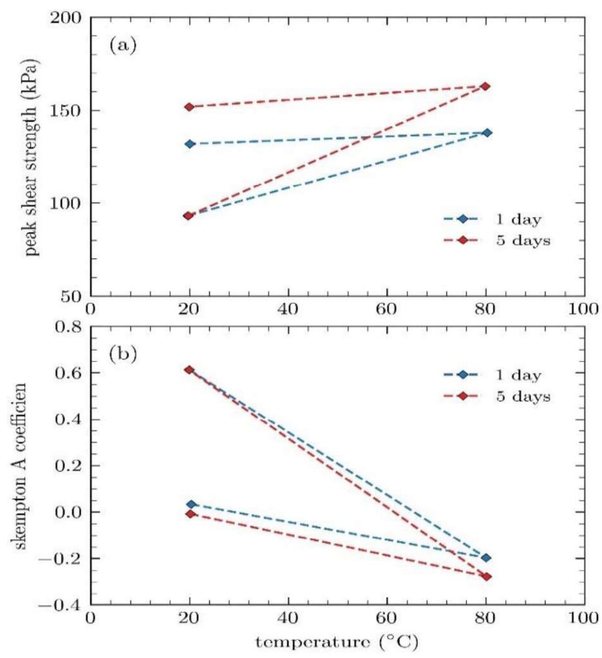

Figure 2. Variation of shear characteristics for the temperature cycle at the confining pressure of $100\ kPa$*: (a) Shear strength and (b) Skempton's A coefficient (Case 2).*

The effect of elevated temperature on the elastic modulus of samples in case 1 is presented in Figure 3. In this figure, the undrained secant modulus is calculated at 50% shear strength (E_{50}). The results indicated that the elasticity modulus was higher in the specimens with longer consolidation time and higher temperatures than those tested at the reference temperature.

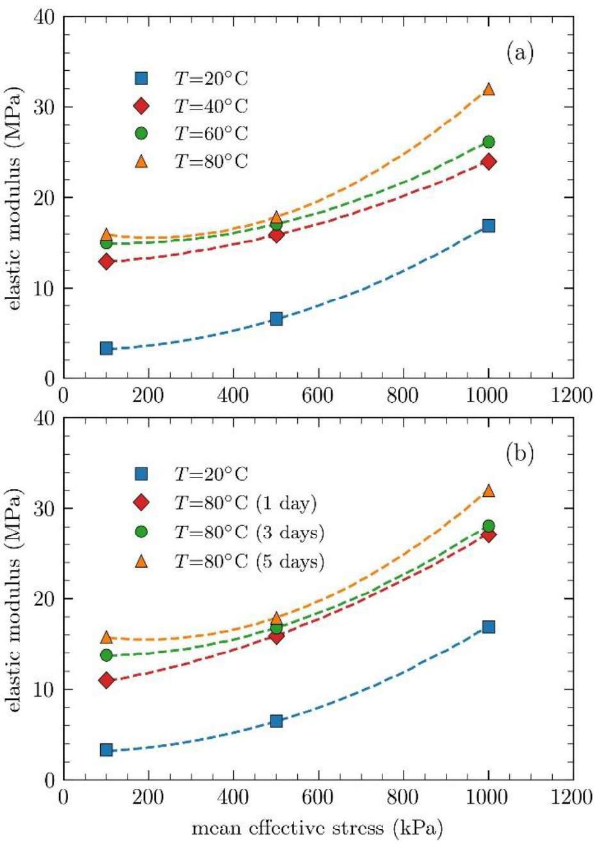

Figure 3. Effect of temperature and consolidation time on the secant modulus at half peak strength.

4 CONCLUSIONS

An experimental program was carried out in a new triaxial cell with a modified thermal triaxial cell to investigate some thermomechanical issues in sand-clay materials. The specimens were installed in thermal triaxial apparatus to experience an undrained triaxial stress path representative of the undrained strength. Two cases of different stress histories were performed. The higher the temperature and heating time, the stiffer and more brittle the triaxial response. The strains also obtained at peak stress decrease while there is a strong gain in peak stress. Increasing the thermal consolidation parameters (time and temperature) reduced pore pressure and transitioned from positive to negative values. The thermal cycle increased the shear strength and experienced a negative pore water pressure that exhibited a transition towards the quasi-structured behaviour.

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