Thermo-hydro-mechanical behavior of an embankment thermal storage

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ABSTRACT

In geotechnical engineering, thermal energy storage in embankments can be considered as a new economically efficient, and environmentally friendly structure for space heating. In these structures, horizontal heat exchanger tubes could be installed inside the different layers of compacted soil to store the heat in the medium during the summer, to be extracted in the winter. Seasonally temperature variations caused by heat exchangers can affect Thermo-Hydro-Mechanical (THM) properties of the compacted soil in the embankment. Both the short and long term behavior of this compacted soil should be investigated. The aim of this study was to investigate the effect of temperature variations in the range of 5° to 50 °C, on THM behavior of a compacted sandy lean clay in saturated state. To achieve this, temperature-controlled oedometric and direct shear tests were performed. The results showed that, the effect of the temperature on mechanical properties are more pronounced under a vertical stress higher than the yield stress. Heating changed the void ratio during consolidation phase but has a negligible effect on the shear characteristics. The results also showed that the cooling slightly changed the shear parameters.

Keywords: Embankment, thermal energy storage, compacted soil, temperature controlled oedometer tests, temperature controlled direct shear tests.

1 INTRODUCTION

Solar energy provides an abundant, clean and safe source of energy with a great potential to produce thermal and electrical energy (Abedin and Rosen, 2011). There are many technologies to convert solar energy into a usable energy for human needs, but this energy has to be available even during the period of low sunlight (Stojanović and Akander, 2010). To face this issue, one solution is solar energy storage in a proper medium during summer, to be preserved and later discharged for utilization in the demanded period for example space heating in winter (Xu et al., 2014 and Li et al., 2018). Several studies have demonstrated the relevance of this method that already used in geologic storage medium. Compacted soils have also recently been used due to their appropriate thermal properties and ease of access (Jradi et al., 2017).

In geotechnical engineering, different types of structures are made of compacted soils, for example, road, rail embankments and dikes. Generally, these linear structures contain several layers of compacted soils as well as horizontal heat exchanger loops can easily be installed in these layers during the construction phase (Boukelia, 2016 and Lahoori et al., 2020). However, when the serviceability of the embankments as thermal energy storage medium starts, the compacted soils are subject to the daily and seasonally temperature variations.

For thermal energy in soil storage mediums, the seasonally temperature variation in one year varied in the range of 5 °C to 50 °C (Hesaraki et al., 2015). These temperature variations can modify the thermo-hydro-mechanical behavior of the soil (Eslami et al., 2014). In particular, in embankments the mechanical behavior (consolidation and shear strength) of a compacted soil under monotonic temperature variation from 5 to 50°C should be investigated.

The compacted soils are unsaturated, thus, during the thermal exploitation phase, suction and temperature are changing simultaneously (Uchaipichat and Khalili, 2009). A suction increased is supposed to improve the structure stability. Therefore, the worst condition will occur when the soil tends toward a saturated state. For example, a huge rainfall infiltration may impact the slope stability of an embankment with reducing the matric suction (Rahardjo et al., 2001 and Li et al., 2019). In this study, the effect of temperature on settlement and shear characteristics of a compacted soil will thus be investigated in the saturated state.

Many researchers evaluated that the effect of a temperature variation on the THM parameters depends on the soil type, the stress history quantified using the overconsolidation ratio (OCR), the thermal stress history (number of thermal cycles) and the applied thermo-

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mechanical path (Burghignoli, 2000, Cekerevac et al., 2004, and Maghsoodi et al., 2020). In terms of consolidation parameters, the yield stress is defined as the limit between elastic and plastic domain. It decreased with temperature increasing from 20 to 90 °C (Tidfors et al., 1989). Regarding the compression and swelling indices (Cc and Cs) are found to be unaffected in the study of Di Donna (2014), whereas François et al. (2007) reported that these indices slightly increased with heating.

In terms of shear strength, the soil samples in overconsolidated condition exhibit an expansion of their volume when they are heated, which lead to a decrease in soil strength. However, the soil samples in normally consolidated condition exhibit a contraction which induces a thermally hardening phenomenon and leads to an increase of soil strength (Yavari et al., 2016). Despite these results, several studies reported that the effect of temperature on the friction angle of the soil is negligible (Yavari et al., 2016), only cohesion increases with heating (Maghsoodi et al., 2019).

Based on the literature most of the investigations are focused on heating from 20 to 90°C. The effect of temperature variations of heating and cooling on both these mechanical (consolidation and shear) parameters are still poorly understood.

This study intended to investigate the thermo-hydro-mechanical behaviour of a compacted sandy lean clay that comes from the Paris region (France). A temperature-controlled oedometric and direct shear devices were used to perform the consolidation and shear test at different temperatures (5, 20 and 50 °C). The effect of heating (20 to 50 °C) and cooling (5 to 20 °C) on consolidation parameters (yield stress, Cc and Cs) and shear characteristics (friction angle and cohesion) are addressed in this study. The experimental campaign allows investigating the structural settlement and slope stability of an embankment by a monotonic heating or cooling.

2 MATERIALS AND METHOD

2.1 Materials

The tested soil was extracted from the Paris region in France. Before being used in the laboratory, the soil is dried, pulverized and sieved through a 2 mm sieve. A complete characterization of the studied soil was given in Boukelia's thesis (2016, table 1). The standard Proctor curve of the material (AFNOR, 1999b) showed an optimum water content (w_{opt}) of 16% and a maximum dry density (ρ_d) of 1.81 $Mg.m^{-3}$. This soil is classified as a sandy lean clay, CL, according to the Unified Soil Classification System (ASTM, 2000).

The reference compaction state in this study is a water content of w=16.3% and a dry density of ρ_d=1.72 $Mg.m^{-3}$ to optimise the thermal storage (Boukelia et al., 2017).

Table 1. Soil properties.

Atterberg limits (ISO NF P94-051, 1993)	
Plastic limit (%)	20.5
Liquid limit (%)	27.2
Plasticity index	6.6
Normal Proctor (AFNOR NF P94-093, 1999b)	
w_{opt} (%)	16.1
ρ_d ($Mg.m^{-3}$)	1.80

2.2 Temperature-controlled oedometric device and program tests

The temperature-controlled oedometric cell included a cylindrical cell of stainless steel (70 mm in diameter) and a piston to apply the vertical stress using a load frame. The deformation of the sample was measured using a linear variable differential transformer (LVDT) sensor with an accuracy of 10^{-2} mm. To impose the desired temperature, a heating-cooling device circulated a fluid in a spiral tube around the soil sample and a K-type thermocouple was placed in the bottom part of the oedometer cell to measure the temperature of the sample during the tests. The system comprised also a volume/pressure controller to measure the pore water pressure at the base of the sample. To minimize the thermal losses, the oedometric cell is insulated with a polystyrene box. Thermal calibration was performed to take into account the effect of temperature on the different parts of the device value.

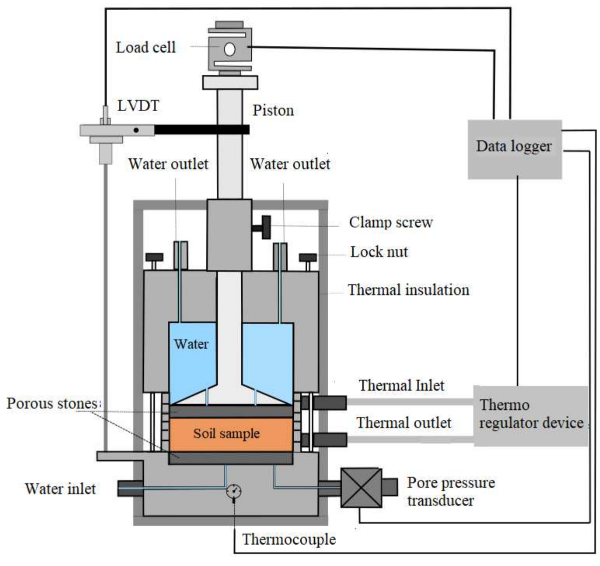

Fig. 1. Temperature-controlled oedometric device.

To perform the oedometric tests, the soil is first wetted at the desired water content, and then compacted directly in the oedometric cell (70 mm in diameter and 20 mm in high). Before being saturated the compacted soil sample was loaded initially under 10 kPa at 20°C. The saturation method consisted in applying a water pressure of 9 kPa through the bottom porous stone (Fig.

1). The saturation state is supposed to be achieved when the hydraulic conductivity reaches a constant value.

After the saturation phase, the samples were slowly heated to 50 °C or cooled to 5 °C to achieve the desired temperature. The heating or cooling phase were applied very slowly (5 °C/h) to avoid excess pore water pressure generation. Then the complete oedometric test consist of 8 successive loading steps from 10 to 1600 kPa and then 4 unloading steps until 100 kPa. The aim of these tests was to investigate the effect of the temperature on the compression index (C_c), the swelling index (C_s) and the yield stress (σ'_p).

2.3 Temperature-controlled direct shear device and program

To perform the direct shear test, the soil at the desired water content was compacted directly in a shear box (0.06×0.06×0.03 m^3). Then, the sample was placed inside a water pan at 20 °C for about one week until reaching the saturation state. The saturation state was checked by measuring the water content of several samples after one week. A constant vertical stress of 10 kPa was applied until reaching a complete consolidation.

The heating system consisted of a heater that controlled the fluid temperature circulating in the lower part of the container (Fig. 2). Therefore, the water temperature in the container reached the same temperature as the circulating fluid. Three thermocouples controlled the temperature through the shear tests. Thermal calibration was performed to take into account the effect of temperature on the different parts of the device (Fig. 2).

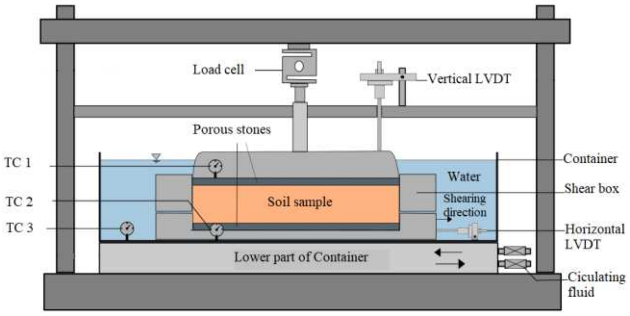

Fig. 2. Temperature controlled direct shear device, where TC 1, 2 and 3 are the thermocouples and LVDT is a linear variable differential transformer.

The heating (20° to 50 °C) or cooling (20° to 5 °C) was applied with a rate of 5°C/h. After that, an effective normal stress (σ'_n) of 50, 100 or 200 kPa was applied on the top of sample. These values correspond to the soil pressure in the depths of 2.5 m, 5 m, and 10 m respectively considering a density of 2 Mg.m^{-3}. After the consolidation phase, the samples were sheared at a displacement rate of 0.020 mm/min. This shear velocity was calculated from the consolidation curve (t_{50}) (time required for the compacted soil sample to achieve 50 percent consolidation under the maximum normal stress, ASTM, 1998), it ensured drained condition inside the direct shear box during shearing and has been verified by other researchers in direct shear device (Di Donna, 2014, Yavari et al., 2016 and Maghsoodi et al., 2019). The aim of this thermo-mechanical path was to investigate the effect of the temperature on the shear parameters (cohesion and friction angle) of the compacted soil samples.

3 RESULTS AND DISCUSSION

3.1 Standard oedometric test

Three standard oedometric tests were done at 5, 20, and 50 °C by applying incremental successive vertical stresses to the soil samples. Figure 3 shows the relationship between the void ratio (e) and the effective vertical stress (σ'_v,) at different temperatures. The yield stress (σ'_p) was obtained using the Casagrande method (Casagrande, 1936). The slope of the normal compression curves at each temperatures is defined as the compression index ($C_c = \Delta e/\Delta log\sigma'_v$) and finally the slope of the unloading curve is defined as the swelling index ($C_s = \Delta e/\Delta log\sigma'_v$). These parameters are presented in table 2.

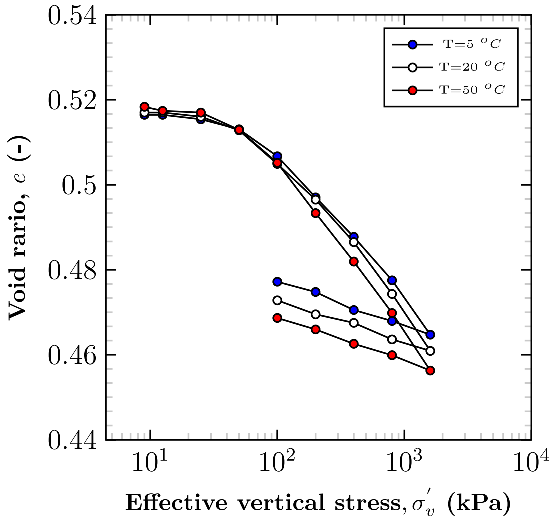

Fig. 3. Void ratio-vertical stress for different temperatures.

Table 2. Consolidation parameters of studied soil for different temperatures.

Test number	Initial void ratio	T (°)	σ'_p (kPa)	C_C	C_s
1	0.516	5	80	0.035	0.01
2	0.517	20	75	0.037	0.01
3	0.518	50	65	0.040	0.013

The yield stress decreases slightly with the temperature increasing whereas the temperature variation has a negligible impact on the compression and swelling indexes. Fig. 4 shows that the obtained results in this study are in agreement with those of other authors (Francois et al., 2007; Di Donna, 2014; Jarad, 2016 and Kaddouri et al., 2019). Also, the decreasing of the yield stress is proportional to the temperature in the range of 5° to 50°C with a slope of -0.33 kPa/°C. This evolution can be linked to the thermal softening of the soil due to the dependence of water properties on temperature. The water viscosity decreases with the temperature increasing which lead to an easier water drainage and to a higher deformation of the solid particles.

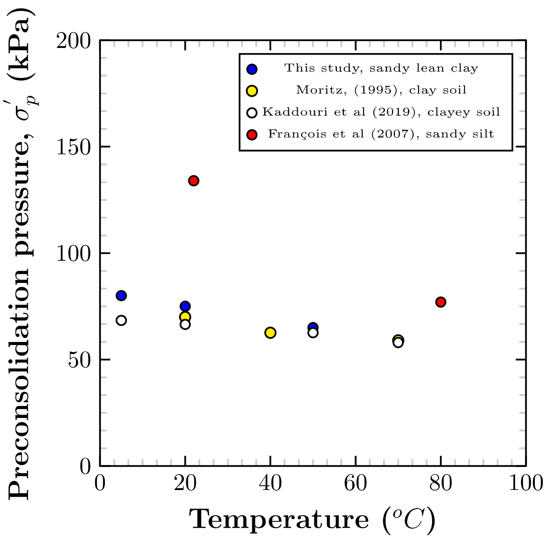

Fig. 4. Yield stress evolution according to the temperature for different studies.

3.2 Direct shear test

To investigate the effect of temperature on shear parameters, direct shear tests were conducted at three different temperatures (5, 20 or 50 °C). After heating or cooling, the consolidation phase started until to reach 50, 100 or 200 kPa. Finally, each sample was sheared with a rate of 0.020 mm/min. Figure 5 shows the direct shear results. To check the repeatability, the test of 200 kPa at 5 °C was done twice. To compare the results, the shear strengths corresponding to 6 mm of shear displacement which is 10 % of sample length were taken for each test and presented in table 3.

Under the effective normal stress of 50 kPa, the shear strength is not affected by heating or cooling (Fig. 5a). The volume of the samples at 20 and 50 °C dilates in the same order of magnitude whereas the dilation during shear of the sample at 5 °C is higher (Fig. 5d). Under σ_n' of 100 kPa, heating from 20 to 50 °C increased the shear strength by 1 %, whereas the cooling from 20 to 5 °C reduced it by 2 % (Fig. 5b). Under this vertical stress (100 kPa), heating and cooling slightly increased the dilation of the soil (Fig. 5e). Under 200 kPa, the heating did not change the shear strength whereas cooling reduced it by 7 % (Fig. 5c). During shearing, the soil sample tended to contract at first, then followed by a dilatation (Fig. 5f).

It can be concluded that the heating improves slightly the shear strength and cooling decreased the shear strength of the compacted soil, effect which was more pronounced under a higher normal stress.

Regarding the volumetric variation during shear phases, at low normal effective stress the compacted soil tends to dilate. However, with the increase of the normal stress, the tendency is more towards contraction. Considering the temperature variation effect, it should be noted that no clear trend was observed. Yavari et al. (2016) mentioned that, in direct shear test, only a very thin layer of soil is subjected to shear and the normal displacement corresponds to the change in volume of the sheared zone. The thickness of this layer can vary from one test to another and can explain this contrasting behaviour.

Figure 6 shows the Mohr-Coulomb plane of the compacted soil at different temperatures. The best-fitting analysis allows to calculate the shear parameters (c and φ) that were presented in table 3. Heating (ΔT=+30 °C) has an almost negligible effect on the shear parameters, whereas cooling (ΔT=-15 °C) increased the cohesion by 4 kPa (30 %) and reduced friction angle of 3 degrees (0.8 %).

These results are in agreement with the results of Yavari et al. (2016), in which the cohesion decreased from 4 to 2 kPa when the temperature varied from 5 to 20°C whereas at 40 °C it remained unchanged (2 kPa). Also different researchers show that a temperature variation has a negligible effect on friction angle (Cekerevac and Laloui, 2004 and Maghsoodi et al., 2020).

Table 3. Shear characteristics of studied soil for different temperatures.

T (°C)	σ_n' (kPa)			c (kPa)	φ (°)
	50	100	200		
5	47.02	78.81	140.73	17.00	31.73
20	47.98	80.26	150.73	13.01	34.42
50	47.99	81.50	152.54	13.12	34.59

Under a qualitative point of view, there is an agreement between the thermo-mechanical response demonstrated by the oedometric test results and shear test results. Both of them show that under a vertical stress higher than the yield stress, the temperature effect is more pronounced. In terms of consolidation behaviour (part 3.1), at 5°C the void ratio variation was less than at the other temperatures (20 and 50 °C) (Fig. 3). Therefore, compacted soil at lower temperature showed a more rigid behaviour and provides low settlement during the consolidation phase. Moreover, the shear test results showed that the compacted soil has a brittle behaviour, it means that the structure of the compacted

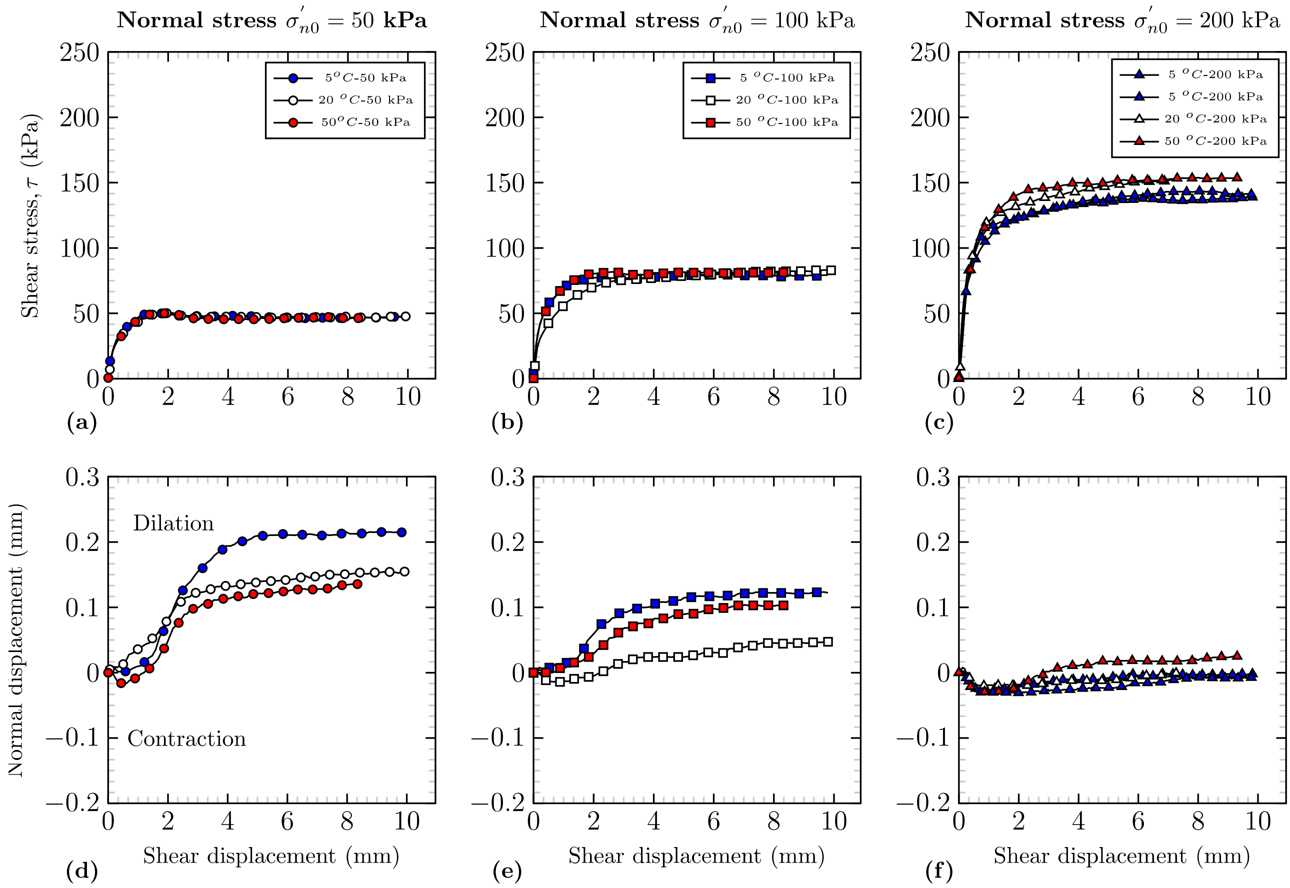

Fig. 5. Effect of temperature on shear stress and normal displacement at three different normal stresses a-d) 50 kPa b-e) 100 kPa and c-f) 200 kPa.

soil was more fragile than at the other temperatures and shows low shear strength than the other temperatures.

This behaviour in the consolidation phase could be explained by the higher viscosity of the pore water at 5 °C. Consequently, the friction between the soil particles increased and their reorganization is restrained.

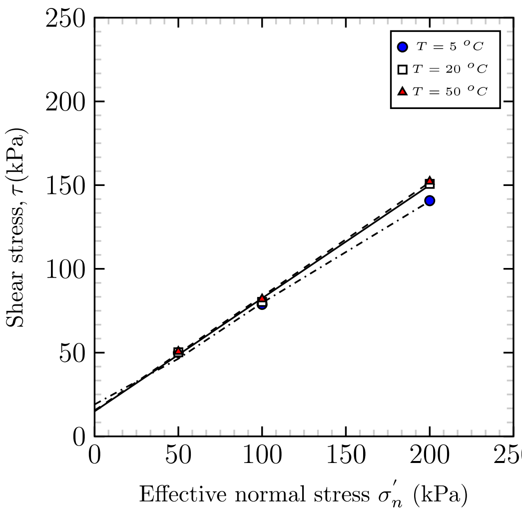

Fig. 6. Mohr-Coulomb plane of compacted soil at different temperatures.

4 CONCLUSION

The goal of this study was to investigate the thermo-hydro-mechanical behaviour of a compacted soil in a saturated state. Therefore, temperature-controlled oedometric and direct-shear devices were used to investigate the consolidation and shear parameters of a compacted soil at different temperatures. The results from oedometric tests showed a temperature dependence of the consolidation parameters. The yield stress decreased slightly with temperature increasing, but the compression index and swelling index were unchanged with temperature variation.

The results from temperature controlled direct shear tests showed that heating from 20 to 50°C had a negligible effect on the shear characteristics of the compacted soil. Contrarily, cooling from 20 to 5°C decreased slightly the shear parameters under a higher normal stress (200 kPa). It can be concluded that the structural stability of the embankment composed of this compacted soil will not be affected by a monotonic thermo-mechanical load in the range of temperature and stress investigated in this study. Further works will be carried out to investigate the effect of the temperature cycles on the mechanical behaviour of this compacted soil.

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