Effect of monotonic and cyclic temperature variations on the mechanical behavior of a compacted soil

Mojdeh Lahoori, Sandrine Rosin-Paumier, Farimah Masrouri

Effect of monotonic and cyclic temperature variations on the mechanical behavior of a compacted soil

Mojdeh Lahoori[1], Sandrine Rosin-Paumier[1], Farimah Masrouri[1]

mojdeh.Lahoori@univ-lorraine.fr

sandrine.rosin@univ-lorraine.fr

farimah.masrouri@univ-lorraine.fr

[1] *LEMTA–CNRS UMR 7563, Université de Lorraine, Vandoeuvre-lès-Nancy F-54500, France*

Corresponding author: Sandrine Rosin (email: sandrine.rosin@univ-lorraine.fr)

Abstract

Settlement and slope stability of an embankment are mechanical aspects that play a major role in structural safety. Due to the tendency towards renewable energy, the embankments can be considered as a suitable medium for thermal energy storage. Using horizontal heat exchanger tubes, the thermal energy will be stored in different compacted soil layers in an embankment. Therefore, this structure can be subjected to daily and seasonally temperature variations due to heat extraction. Cyclic temperature variation can modify the mechanical behavior of compacted soils. Thus this study aims to investigate the effect of monotonic and temperature cycles in the range of 5 to 50 ^oC, on consolidation parameters and shear characteristics of a compacted sandy lean clay. To achieve this, temperature-controlled oedometric and direct shear tests were performed. Results showed that the effect of heating and cooling on mechanical properties is more pronounced under vertical stresses higher than the preconsolidation pressure. By heating, the normal consolidation line shifted to the left and consequently, the apparent preconsolidation decreased. Compression and swelling indexes could be considered independent of temperature variation. Due to the temperature cycles, the volumetric response of the compacted soil in oedometric and shear tests was stress history-dependent. Results of the direct shear tests showed that by temperature variation (heating/cooling and temperature cycles) the cohesion increased and the friction angle remained unchanged.

Keywords: Embankment, thermal energy storage, compacted soil, Thermo-Hydro-

Mechanical behavior, temperature-controlled oedometer tests, temperature-controlled direct shear tests.

1 Introduction

To limit the environmental impact of the production of needed energy, the energy geostructures could provide new and clean solutions to the important issue of global warming for the years to come. These solutions still need to be further studied to provide appropriate techniques for both domestic and industrial energy needs.

Solar energy is an infinite, clean, and affordable source, it has a great potential to produce renewable thermal and electrical energy. Several technologies convert solar energy into a utilizable kind of energy for human needs like space heating. For example, solar energy storage consists of heat storage in a proper medium during summer to be preserved and later discharged for utilization in the winter (Stojanović and Akander 2010; Abedin and Rosen 2011). Several studies have demonstrated that the thermal energy storage in soils is a pertinent technique, due to their appropriate thermal properties and ease of access (Gan 2013; Beier and Holloway 2015).

In geotechnical engineering, different types of structures are made of compacted soils, such as roads and rail embankments. These linear structures contain several layers of compacted soils. To store the heat in an embankment in summer, and extract it in winter (or vice versa), the horizontal heat exchanger loops can be easily installed in these layers during the construction phase (Boukelia 2016; Jradi et al. 2017; Lahoori, Jannot, Rosin-Paumier, Boukelia and Masrouri 2020). For limited size embankments, in which the soil-atmosphere interaction during the charging and discharging season is high, the use of insulation material can be considered in design stage to avoid heat loss (Lahoori, Rosin-Paumier, Stoltz and Jannot 2020).

Generally, the soils and earthen structures are exposed to external daily and seasonally temperature variations. When the serviceability of these structures as thermal energy storage medium starts, they will be subjected in addition to internal seasonal temperature

variations. The temperature variation in soil storage mediums can fluctuate in the range of 10 to 50^oC (Hesaraki et al. 2015). Variations in temperature have an impact on the volume of the constituents, which leads to changes in the deformability of the aggregates and the viscosity of the water. Thus, a heated material would be more deformable and the pore water would be less viscous and more mobile. However, this effect would be more or less important depending on the nature of soil constituents and its structure, inherited from the previous loading history (Cekerevac and Laloui 2004; Uchaipichat and Khalili 2009). This aspect is particularly important in the case of compacted soils. To prevent any damage, such as settlement and slope failure, and also to ensure the long-term structural stability of these energy structures, the effect of temperature variation on their mechanical behavior should be investigated.

Compacted soils are initially set up in an unsaturated state close to the saturation state (degree of saturation between 85 to 95%). During their service life and thermal exploitation in an embankment, the water content, the temperature and the applied mechanical loads are changing simultaneously.

Among different types of external loading, it is well known that landslides, settlements, and disorders of all kinds occur generally as a result of intense rainfall and seepage in embankments (Iverson and Major 1987; Rahardjo et al. 2001; Thibbotuwawa and Weerasekera 2013). Usually, the rainfall decreases the suction and increases the hydraulic conductivity in these unsaturated soils, this accelerates the soil saturation and the pore water pressure increase. As a result, the shear strength and factor of safety of the slope decrease (Rahardjo et al. 2001; Liu et al. 2017; Li et al. 2019).

Based on the aforementioned statements, this study focuses on investigating the thermo-hydro-mechanical behavior of compacted natural soil at saturated state, as in embankments, it is clearly the most critical state. For energy geostructures, a better understanding of the effect of monotonic and cyclic temperature variations on mechanical behavior such as consolidation and shear characteristics of compacted soil is of great importance.

Several researchers investigated the effect of temperature variations on consolidation and volumetric behavior of different types of soils under different stress paths (Tidfors and

Sällfors 1989; Eriksson 1989; Moritz 1995; Burghignoli et al. 2000; Cekerevac and Laloui 2004; Uchaipichat and Khalili 2009; Di Donna and Laloui 2015). These investigations indicated that the effect of temperature on THM behavior of soils depends on the soil nature; the stress history and the thermal variation path.

Regarding the consolidation behavior, heated specimens exhibit a plastic behavior earlier compared to unheated ones, afterwards the elastic domain size reduces and shows a clear soil softening (Tidfors and Sällfors 1989). Thus, Thus, the apparent preconsolidation pressure ($\sigma_p^{'}$) decreases upon heating (Marques et al. 2004; Cekerevac and Laloui 2004). The effect of temperature variation on the compression and swelling indices (C_c and C_s) are found to be negligible in the temperature ranges from 20 to 90 ^oC (Cekerevac and Laloui 2004; Di Donna 2014).

In terms of volumetric behavior under temperature cycles, the soil initially in the normally consolidated state (NC) exhibits a contraction when temperature increases (Burghignoli et al. 2000; Cekerevac and Laloui 2004). However, different observations are reported during the following cooling. In some studies, cooling removes a small part of the thermal contraction caused by heating (Shetty et al. 2019), but in others, during cooling the thermal contraction continues to increase (Campanella and Mitchell 1968; Di Donna and Laloui 2015). Ma et al. (2017) reported that the thermal contraction becomes smaller after 4 or 5 successive heating and cooling cycles.

The soil in an overconsolidated state exhibits a thermal expansion during heating and with subsequent cooling, a reversible behavior is observed. Therefore, the thermal expansion with heating is dissipated (Di Donna and Laloui 2013; Shetty et al. 2019). This reversible behavior was observed with further heating and cooling cycles.

Based on most of the investigations that have focused on the study of the effect of temperature variations between 20 to 90 ^oC, it can be concluded that the preconsolidation pressure is a temperature dependent parameter and decreases with heating. But despite the importance of this parameter in thermal energy storage systems, its variations due to cooling and several heating-cooling cycles are poorly understood.

The other important mechanical characteristics of an energy structure such as a road

embankment are shear parameters: strength and stiffness, where the strength can be expressed in terms of apparent cohesion (c) and friction angle (φ). Although their dependency on temperature variations has been studied in recent years, the results are still controversial.

Cekerevac and Laloui (2004), using a temperature-controlled triaxial device in drained conditions for normally consolidated kaolin clay, have observed an increase of peak shear strength due to temperature increase while the critical state shear strength was independent of temperature. The same observation was reported by Abuel-Naga et al. (2007) for a normally consolidated soft Bangkok clay. Yavari et al. (2016), by performing direct shear tests, showed that for Fontainebleau sand and both normally and overconsolidated kaolin clay, the peak shear strengths were almost independent of temperature (5 to 40 ^oC). Maghsoodi et al. (2020) using a temperature controlled direct shear device, showed that the peak and critical shear strength of normally consolidated kaolin clay increased with a temperature increase from 22 to 60 ^oC, but no temperature dependence was observed for Fontainbleau sand.

The effect of temperature on friction angle (φ) was reported to be negligible in several studies (Moritz 1995; Cekerevac and Laloui 2004; Maghsoodi et al. 2020). But there are different results for the cohesion (c) variation upon heating and cooling cycles. Yavari (2014) found that the cohesion of a kaolin clay at three different temperatures (5, 20, and 40 ^oC) is almost unchanged. On the contrary Maghsoodi et al. (2020) found that the temperature increase from 22 to 60 ^oC increased the cohesion for kaolin clay.

Regarding the mechanical loading cycles, Ng and Zhou (2014) using a temperature controlled device reported that the axial plastic strain accumulated during cyclic loading–unloading is larger at higher temperatures for a silty soil. Very few studies have investigated the impact of thermal cycles on shear characteristics. For example, Yazdani et al. (2019) have investigated the effect of temperature cycles on shear characteristics. Their study is mostly focused on soil-structure interface mechanical behavior. Therefore, the effect of several temperature cycles on the shear behavior of soils needs to be investigated.

The shear characteristics evolution due to the monotonic and cyclic temperature variations depends on several parameters such as material characteristics and soil nature, overconsolidation ratio, experimental conditions, and thermo-mechanical paths. But the results are not numerous enough, and there are still many unanswered questions on this subject.

This experimental study aims to investigate the thermo-mechanical behavior of a compacted sandy lean clay that is currently used in embankment constructions, in the saturated state under different stress paths. Temperature-controlled oedometer and direct shear devices were used to perform consolidation and shear tests under monotonic and cyclic temperature variations. The main aspects of the thermo-mechanical behavior of the compacted soil that are tackled in this study are to investigate the effect of cooling (20 to 5 ^oC), heating (20 to 50 ^oC), and thermal cycles (5-50 ^oC) on consolidation and shear characteristics.

2 Soil properties, devices, and specimen preparation

2.1 Soil properties

The tested soil was extracted from the Paris region in France. X-ray diffractograms analysis reveals that it contains 81% quartz, 7% dolomite, 5% calcite, 5% clayey materials, and 3% feldspar (Boukelia 2016). This material was dried, pulverized, and sieved through a 2 mm sieve before being used for various experiments. According to the particle-size distribution tests, almost 20% of the particles of the soil were smaller than 2 μm, and 41% were smaller than 80 μm (Figure 1). With a liquid limit (LL) of 27% and a plastic limit (PL) of 21%, the plasticity index (PI) was 6% (AFNOR 1993). The standard Proctor test results showed an optimum water content (w_{opt}) of 16% and a maximum dry density (ρ_d) of 1.81 Mg.m^{-3} (Table 1).

The material was classified as sandy lean clay, CL, according to the Unified Soil Classification System (ASTM 2000). In this study, the soil specimens were prepared at a

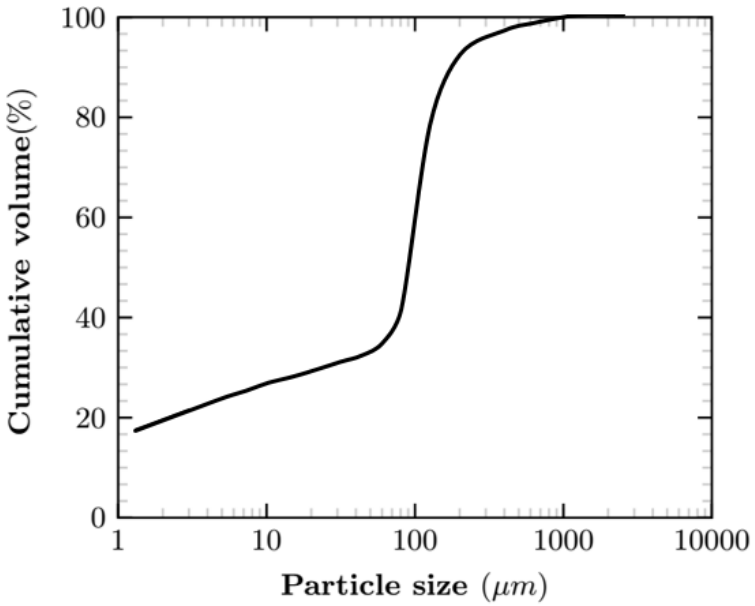

Figure 1: Particle size distribution (Boukelia 2016)

Table 1: Characteristics of the studied soil

Properties	Amount
Plasticity limit (%)	20.5
Liquidity limit (%)	27.2
Plasticity index (%)	6.6
w_{opt} (%)	16.1
ρ_d (Mg/m^3)	1.8
Class of soil	CL
Thermal conductivity (W/m.K)	2.46
Volumetric heat capacity (J/k.m^3)	2.64
Thermal diffusivity (m^2/s)	9.6×10^{-7}

water content (w) of 16.3 % and a dry density ρ_d of 1.79 $Mg.m^{-3}$ in accordance with the optimal thermal condition defined by Boukelia (2016). The dry soil was wetted up to the desired water content by adding the distilled water and stored in plastic bags for almost 3 days before being compacted in the cells for each test.

2.2 Device and specimen preparation: oedometric tests

A temperature-controlled oedometric device was used to investigate the effect of temperature on the consolidation behavior of the studied compacted soil. The system included a cylindrical cell of stainless steel (70 mm in diameter) and a piston to apply the vertical stress using a load frame (Figure 2). The vertical deformation of the specimen was measured using a linear variable differential transducer (LVDT) with an accuracy of 10^{-5} m.

To impose the desired temperature, a heating-cooling device circulated fluid in the spiral tubes around the soil specimen, and a K-type thermocouple was placed in the bottom part of the oedometer cell to measure the temperature of the specimen during the tests. The system comprised also a volume/pressure controller to control the pore water pressure at the base of the specimen. To minimize the thermal losses, the oedometric cell was insulated with a polystyrene box. To maintain a constantly saturated state during tests, a continuous water supply was maintained.

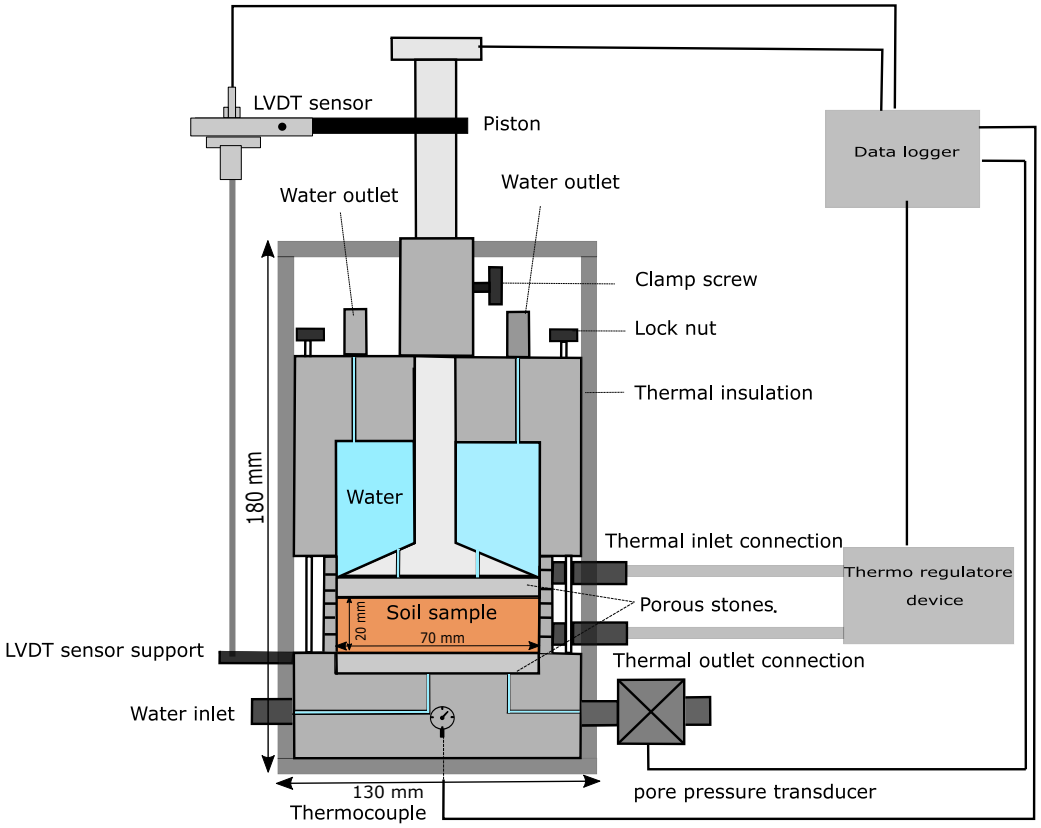

Figure 2: Temperature-controlled oedometric device.

Thermal calibration was performed to take into account the effect of temperature on different parts of the device and corrections were applied to the results. The thermal deformation of the oedometric cell was observed by measuring the vertical displacement of the piston during cycles of heating and cooling under 10 kPa of vertical stress. The device was first heated from 20 ^oC to 50 ^oC, and then was cooled up to 5 ^oC and finally was heated up to 20 ^oC in steps of 10 ^oC. Figure 3 shows the relationship between the measured thermal vertical displacement (Δh_T) of the oedometric cell using LVDT at

different applied temperatures. The heating caused dilation in the oedometric cell, while cooling caused a contraction. A linear equation can be determined as follows:

$$\Delta h_T = -0.0026\Delta T + 0.05 \tag{1}$$

Where ΔT is temperature variation (^oC).

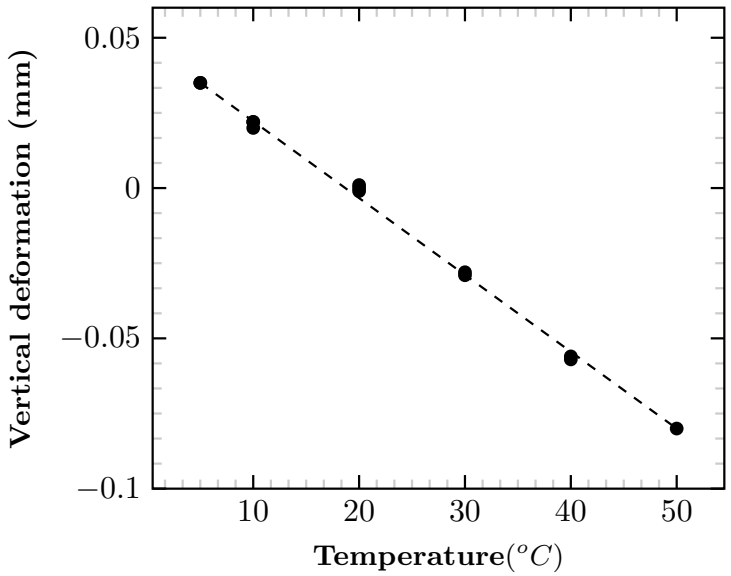

Figure 3: Thermal calibration of temperature-controlled oedometric device.

The abovementioned relationship was used to correct the measurements of the sample deformation during temperature variations by following equation:

$$\Delta h_{T(sample)} = \Delta h_{T(sample+cell)} - \Delta h_{T(cell)} \tag{2}$$

where $\Delta h_{T(sample+cell)}$ is the measured total displacement during heating or cooling phases.

To perform oedometric tests, the soil at the water content 16.3 % was compacted directly in the oedometric cell (70 mm in diameter and 20 mm in height) to reach the target dry density of 1.79 $Mg.m^{-3}$. Then, the saturation phase was started by applying a backwater pressure of 9 kPa through the bottom part of the oedometric cell (through the water inlet, in Figure 2). The saturation phase was performed at 20 ^oC under 9 kPa of vertical stress. To check the saturation state, the hydraulic conductivity was measured

over a long time (7 days) to achieve an equilibrium state, and also the water content of several samples was measured after several days. Afterward, different thermo-mechanical paths were applied, they are presented in detail in section 3.1.

2.3 Device and specimen preparation: direct shear tests

The temperature-controlled direct shear device contains a shear box (60 x 60 x 30 mm) that is placed inside a container filled with water to maintain the saturation state of the samples (Figure 4). The heating-cooling system circulates fluid at the desired temperature under the container. The temperature is checked using 3 different thermocouples placed: in the upper half of the shear box; in the lower half of the shear box and the container. A piston applies the normal stress σ_n (kPa) on the top of the soil specimen using a load frame. The shear displacement and the normal displacement were measured using two linear variable differential transducers (LVDT) (Figure 4). To obtain the real volume change of the soil sample, the thermal calibration of the different parts of the device was performed.

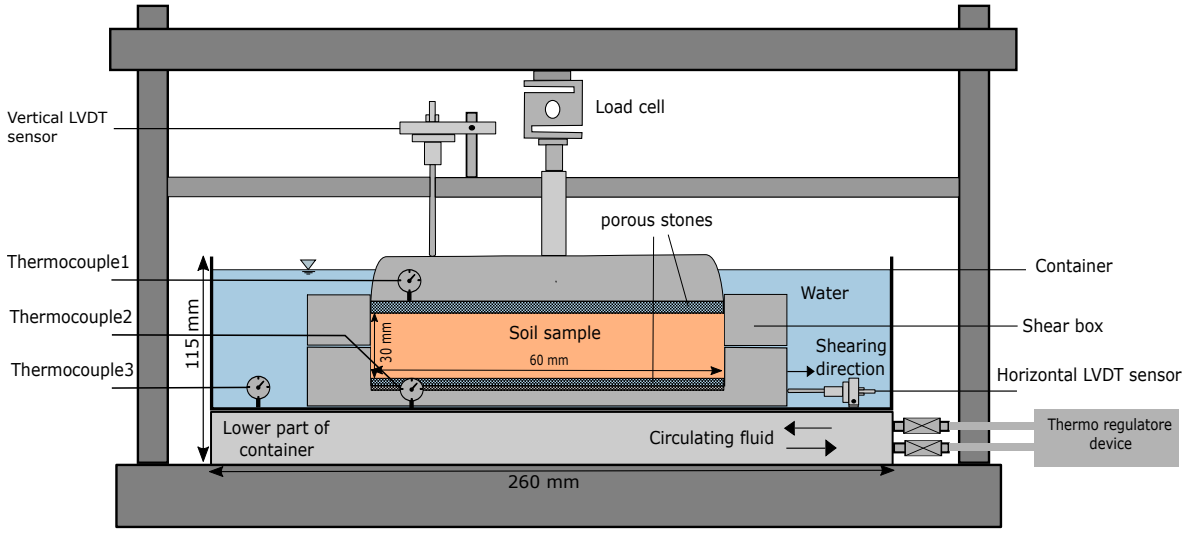

Figure 4: Temperature-controlled direct shear device.

Before direct shear tests, the soil at the initial water content (16.3 %) was compacted directly in the shear box at the density of 1.79 $Mg.m^{-3}$. The specimens were saturated by leaving them inside a water container at 20 ^oC. The saturation level was checked by measuring the water content of different specimens after several days. After one week, the

measured water content was close to the estimated water content of a saturation state. This duration was repeated for all the samples.

3 Experimental programs

The experimental programs to take into account the effect of cooling (20 to 5 ^oC), heating (20 to 50 ^oC), and several heating-cooling cycles in the range of 5 to 50 ^oC on consolidation and shear behavior are presented in the following.

3.1 Consolidation program

3.1.1 Monotonic thermo-mechanical paths

Standard oedometric tests were conducted at different temperatures to investigate the effect of temperature on the consolidation parameters as compression index (C_c), swelling index (C_s), and apparent preconsolidation pressure ($\sigma_p^{'}$). After the saturation phase, one reference standard oedometric test at 20 ^oC was performed (test number 1 in Table 2). The specimen was loaded by applying successive vertical stress increments in different steps in the range of 9 to 1600 kPa and then was unloaded to 100 kPa. From ASTM (2011), each step took 24 hours, and from t90 of settlement versus time curves, the end of consolidation was determined. For oedometric tests at different temperatures, the soil specimen was cooled from 20 to 5 ^oC or heated up from 20 to 50 ^oC with a heating/cooling rate of 5 ^oC/h after the saturation phase. The heating/cooling rate was sufficiently slow to avoid excess pore water pressure generation due to the temperature variation (Cekerevac and Laloui 2004; Shetty et al. 2019). Then the complete oedometric tests were performed (tests number 2-3 in Table 2).

3.1.2 Cyclic thermo-mechanical paths

The tests numbers 4 to 7 in Table 2 were supposed to reproduce the volumetric response of compacted soil element in different depths of an embankment which is under internal

Table 2: Experimental programme for consolidation tests (L=loading, U=unloading, C=cooling, H=heating and TC = thermal cycles).

Test number	Test type	Temperature (^oC)	Vertical effective stress (kPa)	OCR before TC	TC (^oC)
1	L-U	20	9-1600-100	-	-
2	C-L-U	5	9-1600-100	-	-
3	H-L-U	50	9-1600-100	-	-
4	L-4 TC	20	9	8	5-50
5	L-4 TC	20	9-170	1	5-50
6	L-4 TC	20	9-400	1	20-50
7	L-U-4 TC	20	9-1600-100	16	20-50

and external seasonal temperature variations.

Therefore, to simulate the effect of external seasonal temperature variation due to the soil-atmosphere interaction, compacted soil sample in test number 4 (Table 2) was subjected to 4 temperature cycles in the range of 5 to 50 ^oC after saturation phase under 9 kPa. The thermal load (heating and cooling) was applied by successive increments of ΔT=10 ^oC (5 ^oC/h).

The test numbers 5 to 7 consider the effect of internal temperature variation due to the heat transfer from a horizontal heat exchanger that is commonly horizontal installed at $2m$ from the base. Considering $10m$ height embankment, the total vertical stress is 170 kPa (20.8 $kN.m^{-3}$ x 8 m). Therefore, test number 5 (Table 2) was thus done by applying the vertical stress from 9 to 170 kPa, and then 4 temperature cycles (5 to 50 ^oC) were applied. Besides these conditions, during the lifetime of the embankment, the compacted soil may be loaded or unloaded. Test number 6 (Table 2) simulated a subsequent loading of the compacted soil. Therefore, the soil sample was vertically loaded from 9 to 400 kPa and then 4 temperature cycles (20 to 50 ^oC) were applied (test number 6 in Table 2). To reach a highly overconsolidation state (OCR=16) four temperature cycles in the range of 20 to 50 ^oC were applied after a loading (1600 kPa) and unloading of 100 kPa (test number 7 in table 2).

3.2 Direct shear program

3.2.1 Monotonic thermo-mechanical paths

The direct shear tests at different temperatures were conducted to investigate the effect of the cooling and heating on shear parameters. After the saturation phase at 20 ^oC, the normal stress was applied to the compacted soil (paths $0-1$ in Figure 5). Three values of initial normal stresses ($\sigma_n^{'}$=50, 100, 200 kPa) were chosen. These values correspond to the soil pressure in the depths of 2.5 m, 5 m, and 10 m in an embankment assuming a density of 20.8 $kN.m^{-3}$. After the consolidation phase, the shear test at 20 ^oC was done (paths $1-2$ in Figure 5, tests 1-3, Table 3). From the settlement curve and the time required for the specimen to achieve 50 percent of its consolidation under the maximum normal stress (t_{50}) a shearing rate of 0.02 $mm.min^{-1}$ was calculated (ASTM 1994). This slow rate applied for the shear test was supposed to ensure drained conditions during shearing. To take into account the effect of temperature variation on shear parameters, after the consolidation phase, the cooling or heating phase was applied (paths $1-1^{'}$ and $1-1^{''}$ in Figure 5). Finally, when the soil volumetric variation stabilized, the specimens were sheared with a rate of 0.02 $mm.min^{-1}$ (paths $1^{'}-2^{'}$ and $1^{''}-2^{''}$ in Figure 5, tests 4-10, Table 3).

3.2.2 Cyclic thermo-mechanical paths

The thermal cycles under constant normal stress were performed on compacted soil specimens in the direct shear box to evaluate the variation of shear parameters (cohesion and friction angle) after the thermal cycles. As the monotonic thermo-mechanical path, after the saturation phase at 20 ^oC, three normal stresses ($\sigma_n^{'}$=50, 100, 200 kPa) were applied on different compacted soil specimens at 20 ^oC. After the consolidation phase, 5 thermal cycles in the range of 5 to 50 ^oC were applied by a successive increment of ΔT=10 ^oC (5 ^oC/h). After thermal cycles, when the thermal volume change stabilized, the specimens were sheared at 20 ^oC with a displacement rate of 0.02 $mm.min^{-1}$ (tests 11 to 13, Table 3).

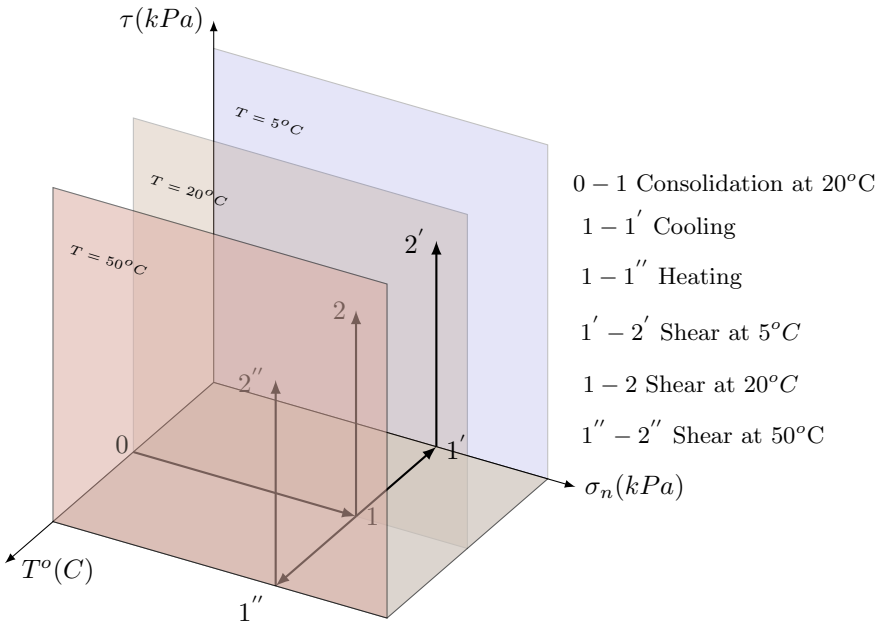

Figure 5: Thermo-mechanical path for direct shear tests at different temperatures.

4 Experimental results

This part presents the results from oedometric and direct shear tests under different thermo-mechanical paths. The following part will be dedicated to the scientific discussion.

4.1 Thermo-mechanical results for oedometric tests

4.1.1 Monotonic thermo-mechanical oedometric results

Three standard oedometric tests at different temperatures were carried out (5, 20, and 50^oC). The void ratios for all of the specimens after saturation remained unchanged due to the zero swelling potential of this compacted soil. The void ratio variations after cooling and heating were negligible.

Figures 6a and b show the normalized settlement and void ratio variations against the vertical effective stresses at different temperatures respectively. The results show that, with temperature increase at vertical stresses higher than 100 kPa, the vertical displacement increased, and at the same time the void ratio decreased (Figure 6b). These

Table 3: Experimental programme for direct shear test (TC=thermal cycles)

Test number	Density (Mg/m^3)	Type	Temperature ^oC	effective normal stress (kPa)
1	1.77	Loading-Shearing	20	50
2	1.76	Loading-Shearing	20	100
3	1.76	Loading-Shearing	20	200
4	1.75	Loading-Cooling-Shearing	5	50
5	1.76	Loading-Cooling-Shearing	5	100
6	1.77	Loading-Cooling-Shearing	5	100
7	1.76	Loading-Cooling-Shearing	5	200
8	1.75	Loading-Heating-Shearing	50	50
9	1.77	Loading-Heating-Shearing	50	100
10	1.76	Loading-Heating-Shearing	50	200
11	1.78	Loading-5 TC-Shearing	20 (5-50)	50
12	1.78	Loading-5 TC-Shearing	20 (5-50)	100
13	1.78	Loading-5 TC-Shearing	20 (5-50)	200

results show that the heated soil becomes more compressible and the soil capability to support a vertical stress decreases, as a consequence the normal consolidation line moves to the left. Therefore, for the studied soil, the consolidation behavior could be considered as temperature-dependent and with temperature increase, a thermal softening could be expected.

Table 4: Consolidation parameters of studied soil at different temperatures.

Temperature ^oC	Initial void ratio	C_c	C_s (unloading)	$\sigma_p^{'}$ (kPa)
5	0.516	0.035	0.01	80
20	0.517	0.037	0.01	75
50	0.518	0.040	0.013	65

From the results obtained in standard oedometric tests at different temperatures (Figure 6b), the slope of the normal compression lines defined as compression index ($C_c = \Delta e/\Delta log\sigma_v^{'}$), and the slope of the unloading lines defined as a swelling index ($C_s = \Delta e/\Delta log\sigma_v^{'}$) were obtained and are presented in the Table 4. The results showed that their variation with temperature appears as they changed very slightly with temperature variation.

The apparent preconsolidation pressure $\sigma_p^{'}$ was evaluated using the Casagrande method (Casagrande 1936) for each standard oedometric curves at each temperatures (5, 20, 50

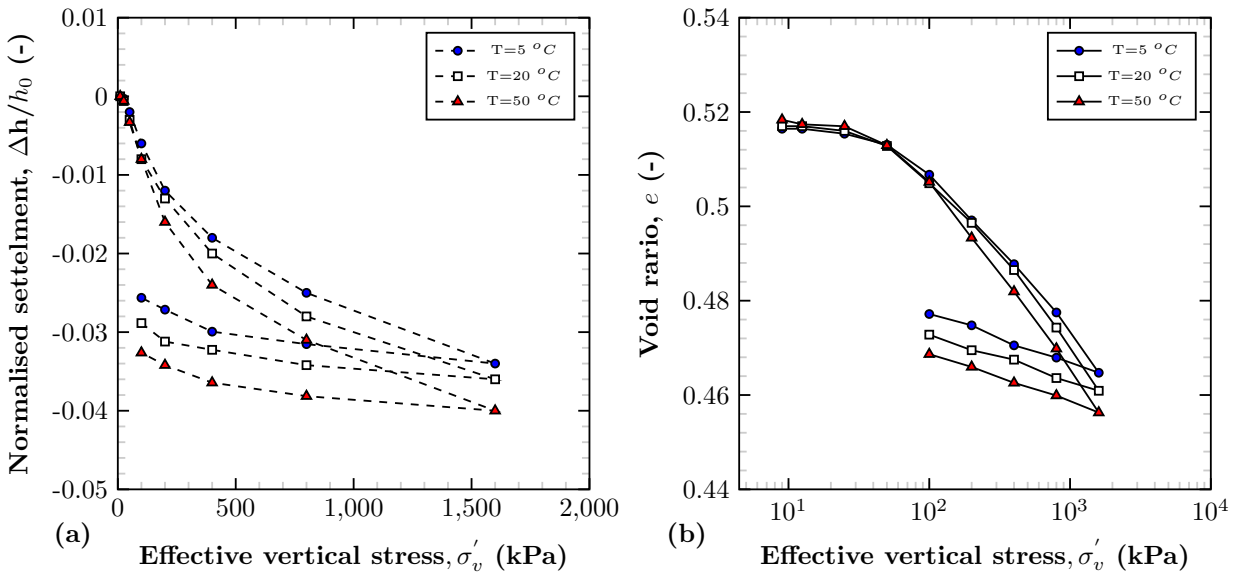

Figure 6: (a) normalized settlement and (b) void ratio variations against effective vertical stress at different temperatures.

^oC). The results presented in Table 4. The preconsolidation pressure $\sigma_p^{'}$ reached 80, 75, and 65 kPa at 5, 20 to 50 ^oC respectively.

From the results of void ratio variations against vertical stress the hydraulic conductivity was calculated for each load increment at different temperatures using the following equation:

$$k = C_v m_v \gamma_w \tag{3}$$

where k is the hydraulic conductivity $(m.s^{-1})$, C_v is the coefficient of consolidation $(m^2.s^{-1})$, m_v is the coefficient of volume compressibility (kPa^{-1}) and γ_w is the unit weight of water at a given temperature $(kN.m^{-3})$.

The hydraulic conductivity as function of void ratio is shown in Figure 7 (a). Figure 7(a) shows that when the void ratio decreased, the hydraulic conductivity decreased due to the increasing density. For example, in Figure 7(a), under 1600 kPa of vertical stress, the hydraulic conductivity increased as temperature increases whereas the void ratio decreased. Delage et al. (2009) observed the same trend for hydraulic conductivity of Boom clay under different temperatures. They pointed out that these results may be due to the coupled effect of changes in water properties and porosity due to the temperature variation. However, Morin and Silva (1984) and Abuel-Naga et al. (2005) reported that

the impact of soil volume change due to the temperature variation is too small to be considered as a reason for the change of hydraulic conductivity at elevated temperature (90 °C). With temperature increase, the viscosity of water decreases and leads to an increase in the soil hydraulic conductivity (Hillel 1980) therefore the water flows are more freely through the porous network.

Based on the hydraulic conductivity test results at different temperatures, an equation is proposed to determine the intrinsic permeability K (m^2):

$$k = \frac{K\gamma_w(T)}{\mu(T)} \tag{4}$$

where k is the hydraulic conductivity $(m.s^{-1})$, γ_w is the unit weight of water $(kN.m^{-3})$, μ is the water viscosity $(Pa.s)$ and T is the temperature (K). According to the literature, the viscosity of water in effective porosity decreases at higher temperature:

$$\mu(T) = -0.00046575Ln(T) + 0.00239138 \tag{5}$$

Figure 7 (b) shows the variation of intrinsic permeability against the void ratio. Based on this figure a linear relationship was evidenced between the intrinsic permeability and the void ratio variations. These results were in agreement with the study of Li et al. (2018) on intact and remolded sensitive clay and with the study of Delage et al. (2009) on Boom clay. Therefore, the temperature dependence of water viscosity could partly explain the hydraulic conductivity variations upon thermal solicitations.

4.1.2 Thermal cycles effect on the volumetric variation of studied compacted soil

The results of volumetric variation against temperature cycles under 9 kPa are presented in Figure 8a (test number 4, Table 2). With heating from 20 to 50 ^oC the volumetric response was almost negligible whereas, during cooling from 50 to 5 ^oC the sample dilated slightly. With further temperature cycles, the soil specimen showed a thermo-elastic response and the volumetric variations were reversible. This reversible behavior corresponds to the thermo-elastic expansion and contraction of the solid skeleton.

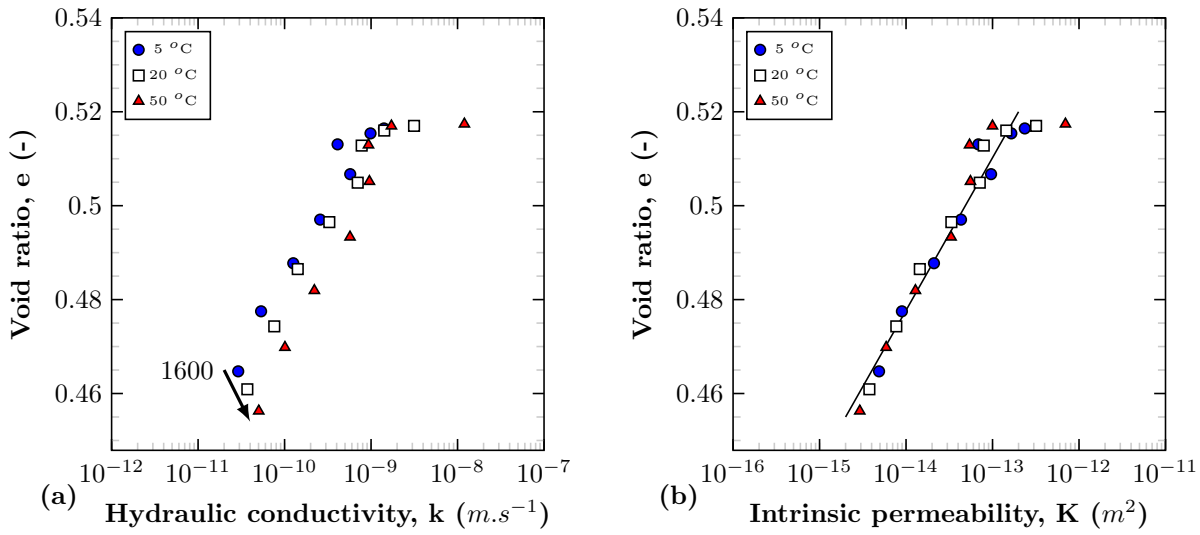

Figure 7: Effect of the temperature on (a) hydraulic conductivity (k) and (b) intrinsic permeability (K).

Under 170 kPa the soil was in normally consolidated condition (void ratio after temperature cycles=0.5) and after first heating (20 to 50 ^oC), the specimen contracted as a volume decrease of 0.13% was observed (Figure 8a). To determine the elastic or plastic nature of thermal loading, after heating, the sample is cooled down to 5 ^{o}C and the volume of the specimen slightly decreased (0.17%). The volume variations during the first thermal cycle (20-50-5 ^oC) were irreversible. But this thermal contraction decreased cycle by cycle and after four thermal cycles, the deformation was stabilized and an elastic behavior was reached. In Figure 8a, it appears that the part of the curve under 20 ^0C is superimposed. In the following, the temperature cycles were applied in the range of 20 to 50 ^0C.

After thermally induced volume changes verification for effective in-situ stress states, two extreme cases were applied. In test number 6 under 400 kPa (NC state, void ratio after temperature cycles=0.48), 4 thermal cycles (20 to 50 ^oC) exhibited a thermal plastic contraction increasing when the number of thermal cycles increased (Figure 8b). In highly OC state (OCR=16) in test number 7 (Table 2), again 4 thermal cycles in the range of 20 to 50 ^oC were applied. In this state, after a slight deformation, the soil specimen showed a reversible volumetric response (Figure 8b).

The elastoplastic deformation due to the thermal cycles at OC (at 9 kPa) and NC (at 170 and 400 kPa) states leads to a void ratio variation at constant vertical stress. To

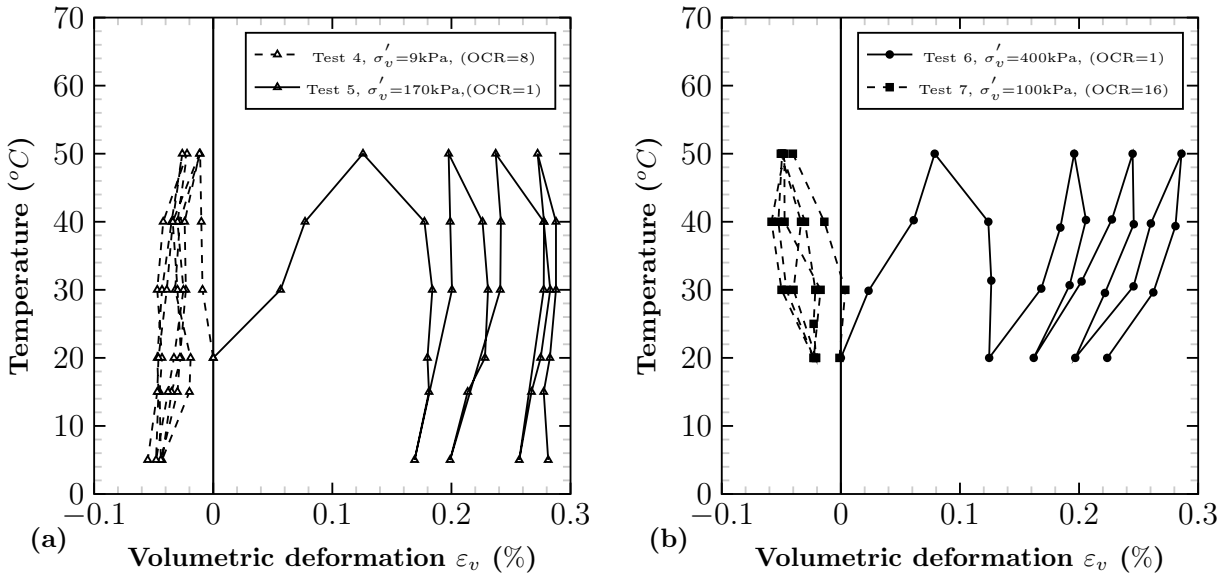

Figure 8: Volumetric deformation during thermal cycles under a) 9 kPa (test 4, OCR=8) and 170 kPa(test 5, OCR=1) b) 400 kPa(test 6, OCR=1) and 100 kPa (test 7, OCR=16)

compare the effect of thermal cycles on soil with a reference oedometric test at 20 ^oC, the evolution of normalized void ratios versus effective vertical stress for both types of tests with thermal cycles and reference oedometric tests, are depicted in Figure 9. Figure 9a shows that the void ratio increased after the thermal cycles under 9 kPa (OC state). To detect the effect of this variation on the subsequent loading, the specimen was then loaded vertically. The whole curve is slightly higher than the reference test (black points). The slope of the consolidation line (C_c=0.036) was the same as the reference test, and the temperature cycles had a negligible effect on the apparent preconsolidation pressure.

Figure 9b and 9c show the void ratio variations for applied thermal cycles under 170 and 400 kPa respectively (test 5 and 6, Table 2). The void ratios, before applying thermal cycles, coincided with the reference oedometric test at 20 ^oC. After thermal cycles, the void ratio in NC state decreased for both tests. These variations are due to the thermally induced plastic deformation that can be considered as a thermal hardening. These void ratios corresponded to a void ratio in higher vertical stress for the reference test at 20 ^oC. For instance, in Figure 9b the normalized void ratio after thermal cycles under 170 kPa was 0.95 which corresponds to vertical stress of 230 kPa for the reference test at 20 ^oC (blue point in Figure 9b). Therefore, when the specimen is subjected to thermal cycles

it behaves like an over-consolidated soil. After this loading, the specimens were loaded vertically and the void ratios for both tests reached the same void ratio as the reference test. The slope of the subsequent loading line after thermal cycles (slope of ac line in Figure 9b) is 0.021 while the slope for the normal consolidation line at 20 ^oC is 0.037.

4.2 Thermo-mechanical results for direct shear test

4.2.1 Monotonic thermo-mechanical direct shear results

In this section, the effect of cooling and heating on shear characteristics is investigated. In temperature-controlled direct shear tests, after the saturation phase, the consolidation phase was started and the specimen was loaded vertically at three different normal stresses $\sigma_n^{'}$=50, 100, and 200 kPa at 20 ^oC. After this consolidation phase, a heating or cooling phase (5 ^oC/h), was applied to the compacted soil specimens. The cooling phase was conducted from 20 to 5 ^oC and the heating phase from 20 to 50 ^oC. The results showed that the cooling phase had a negligible effect on the volumetric deformation of the specimens whereas during heating, the specimens contracted and the volumes of the specimens decreased slightly. Figure 10a shows the volumetric deformation due to the thermal softening of the samples in the shear box. The volume of the specimens decreased by 0.07, 0.12, and 0.14 % for the normal stresses of 50, 100, and 200 kPa respectively.

When the thermal volumetric deformation stabilized, the compacted soil was sheared with a rate of 0.02 mm/min. Figure 11 shows the variation of the shear strength against shear displacement for $\sigma_n^{'}$=50, 100, and 200 kPa at 5, 20, and 50 ^oC. To ensure the quality of the results, several tests were duplicated, for example, the test under $\sigma_n^{'}$=100 kPa at 5 ^oC (Figure 11b). Under normal effective stress of 50 kPa and 100 kPa, the shear strengths were not affected by heating or cooling (Figure 11a). However, the heated and cooled specimens showed a higher dilatation than the specimen at 20 ^oC (Figure 11d). Under 200 kPa, the shear stress was not affected by heating whereas cooling reduced it by 9 % (Figure 11c). For these samples during shearing, the soil specimen slightly contracted at first, then this contraction was followed by a negligible dilatation (Figure 11f).

To obtain the shear characteristics (cohesion, c and friction angle φ), the shear stress

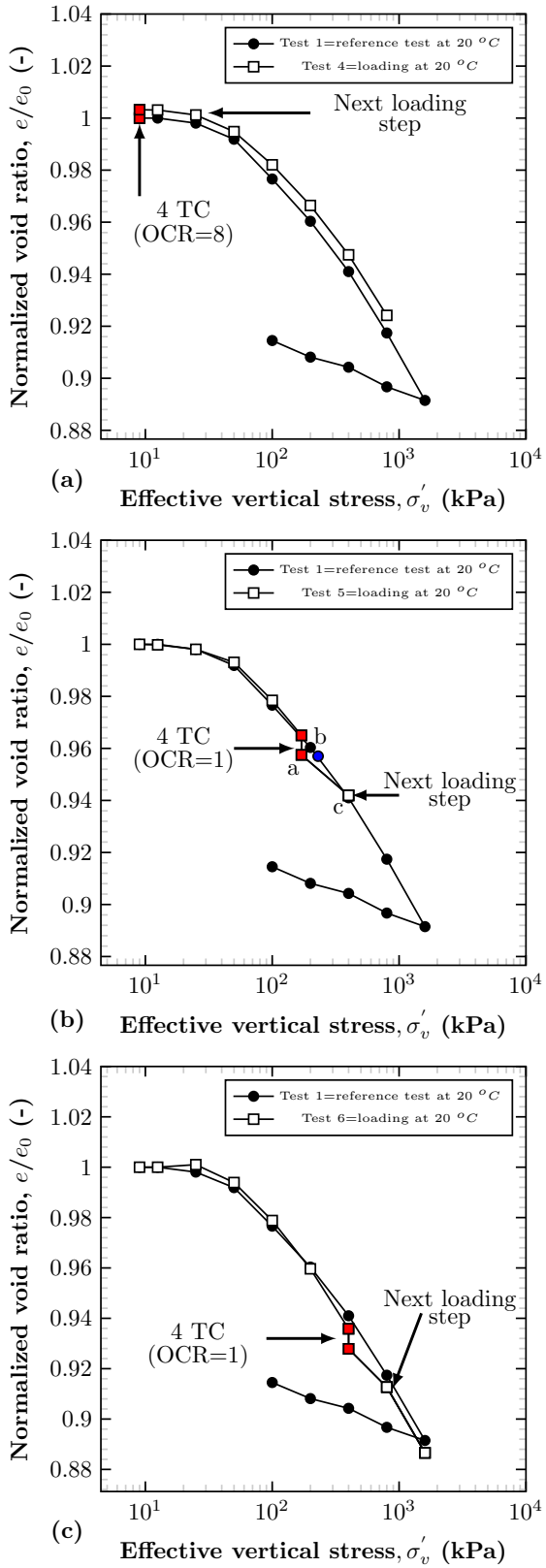

Figure 9: Void ratios variation after thermal cycles under (a)9 kPa (b) 170 kPa (b) 400 kPa, TC=temperature cycles.

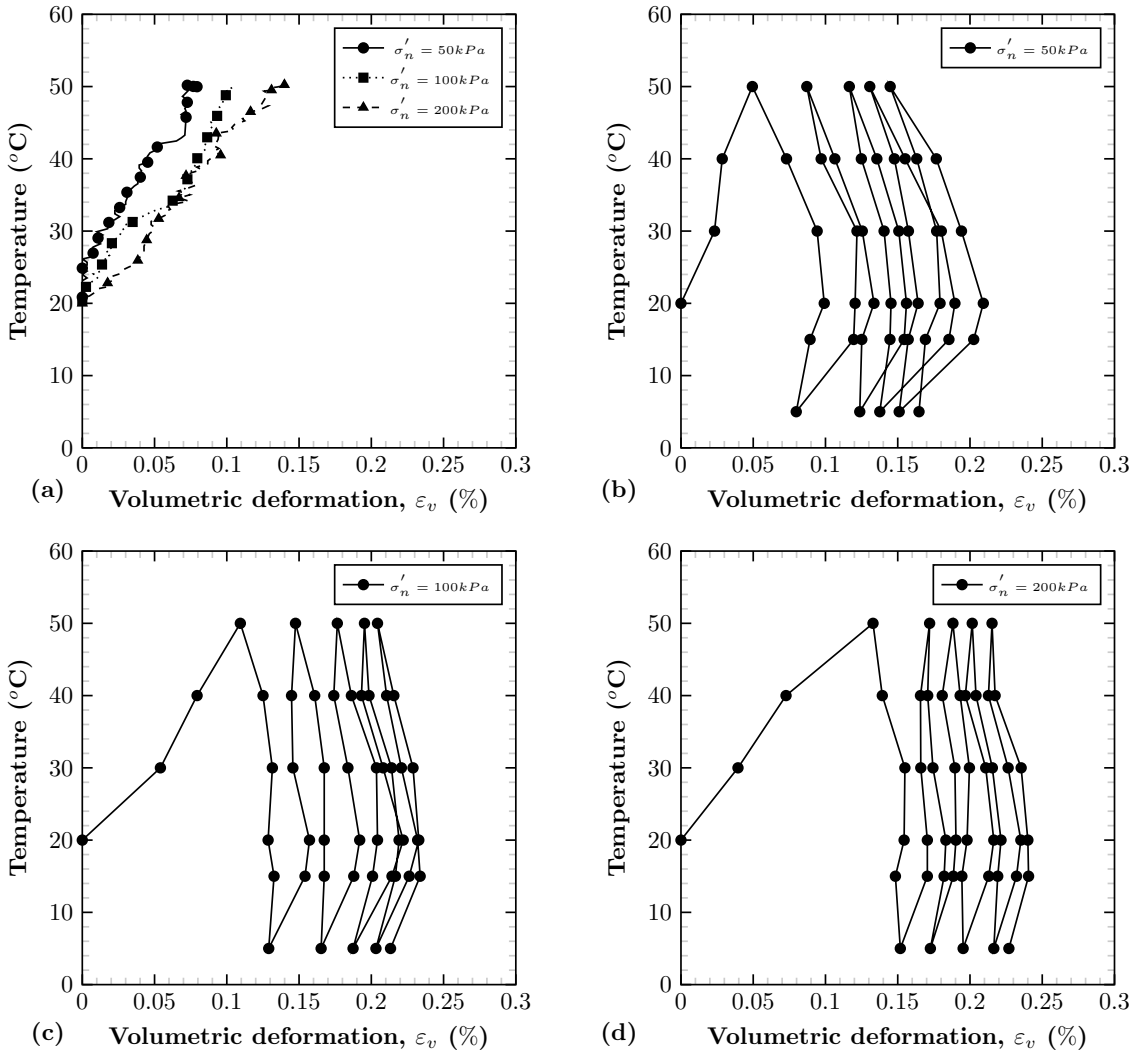

Figure 10: Thermal volumetric deformation (a) during heating from 20 to 50 °C (b), (c) and (d) during 5 thermal cycles at $\sigma_n^{'}$ = 50, 100 and 200 kPa respectively.

corresponding to 10 % of the sample length was taken for each test and is presented in Table 5. Figure 12 shows the Mohr-Coulomb plane for the studied soil at different temperatures. The results show that cooling ($\Delta T = -15^oC$) changed the shear characteristics: the cohesion increased from 13.0 to 20.5 kPa and the friction angles decreased slightly from 34.4^o to 30.5^o. The heating ($\Delta T = +30^oC$) increased slightly the cohesion by 4 kPa (from 13.0 to 17.4 kPa) and the friction angle was not affected.

It can be concluded that the thermal volumetric deformation during heating did not affect the shear strength but cooling decreased it and this behavior was more pronounced under high normal stresses. Regarding the volumetric variation during the shear phase, at low normal effective stresses, the compacted soil tended to dilate. However, with

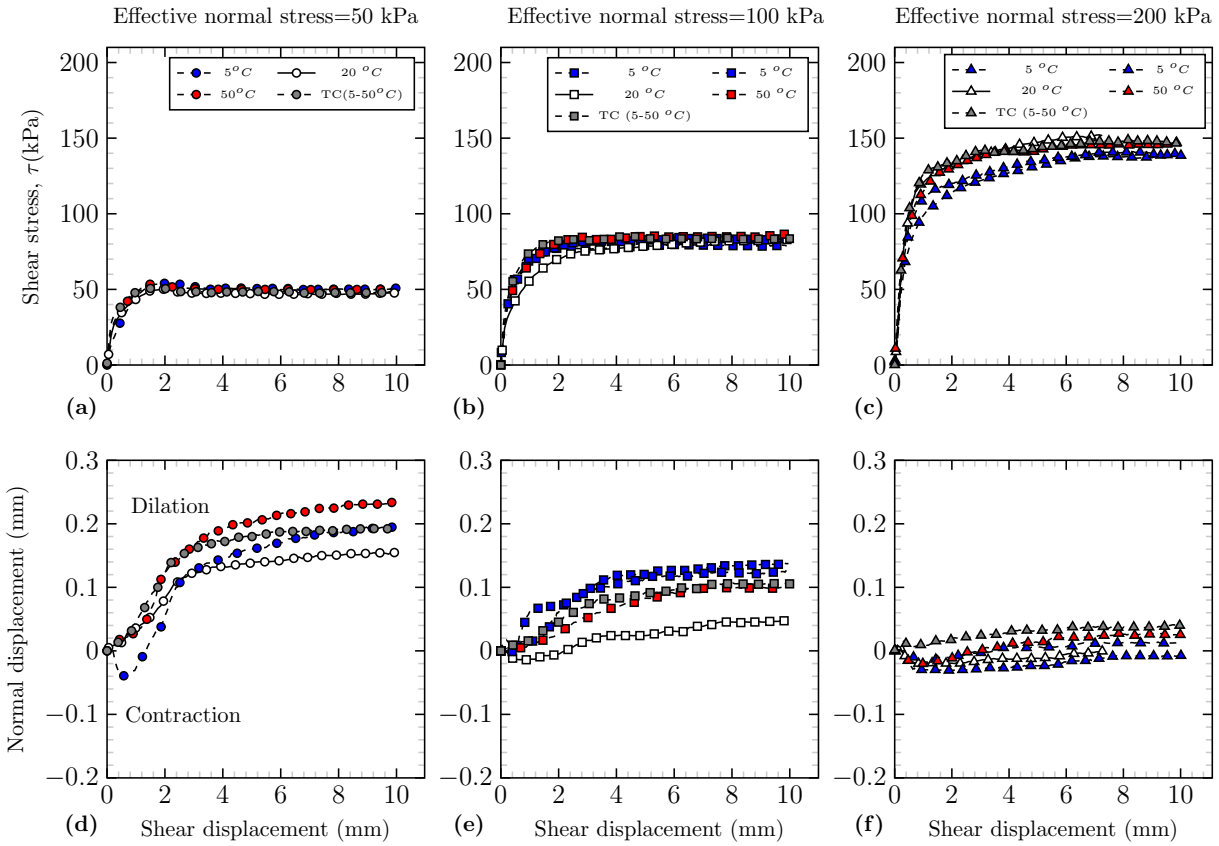

Figure 11: Effect of temperature on shear stress and normal displacement at three different effective normal stresses a-d) 50 kPa b-e) 100 kPa and c-f) 200 kPa, TC=temperature cycles.

Table 5: Shear characteristics of studied soil for different temperatures.

T (^oC)	τ (kPa)			c (kPa)	φ (^{o})
	$\sigma_n^{'}$= 50 kPa	$\sigma_n^{'}$=100 kPa	$\sigma_n^{'}$=200 kPa		
5	49.7	79.0	137.0	20.6	30.5
20	48.0	80.5	150.5	13.0	34.4
50	49.8	84.7	149.5	17.4	33.5
TC(5-50)	48.6	83.7	146.0	17.4	33.0

increasing the normal stress, this tendency is fading.

4.2.2 Cyclic thermo-mechanical direct shear results

For thermal cyclic tests after saturation, the same normal stresses as monotonic section ($\sigma_n^{'}$=50, 100, and 200 kPa) were applied. After reaching the desired normal stress, the compacted soil samples were subjected to temperature cycles: they were first heated up from 20 to 50 ^{o}C then cooled down from 50 to 5 ^{o}C and subsequently followed by 4 temperature cycles from 5 to 50 ^{o}C.

Figure 10b, c, and d show the volumetric deformation due to the temperature cycles

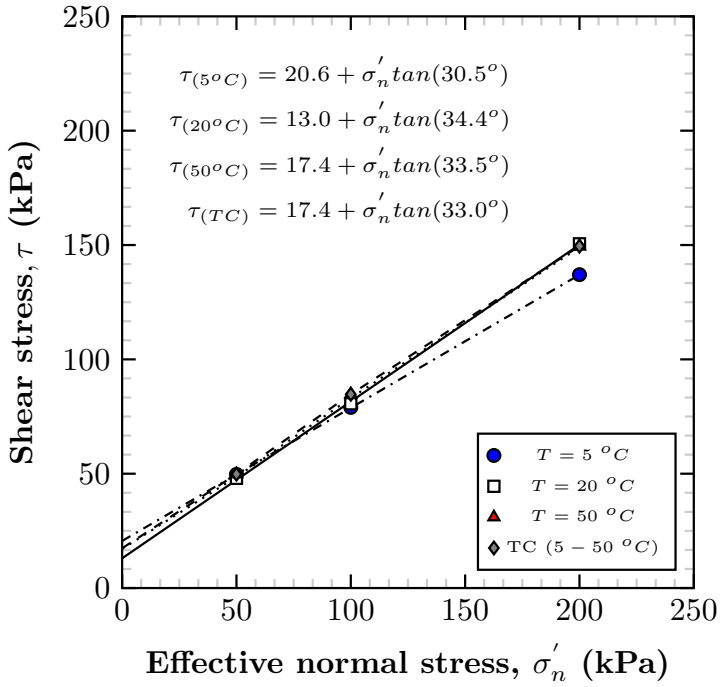

Figure 12: Shear stress against effective normal stress at $T = 5\ ^oC$, $T = 20\ ^oC$, $T = 50\ ^oC$ and after 5 TC (temperature cycles, 5-50 ^oC).

under each normal stress. The compacted soil upon heating from 20 to 50 ^oC contracted by 0.05, 0.11, and 0.14 % under normal stress of 50, 100, and 200 kPa respectively. This order of magnitude is coherent with the results of monotonic thermo-mechanical paths as is shown in Figure 10a. After that, the samples cooled down to 5 ^{o}C and slightly contracted. The contraction of the sample upon the first heating was found to be irreversible. The first cycle caused a higher contraction compared to subsequent cycles (Figure 10b, c, and d). The final thermal contractions after 5 thermal cycles were 0.16 %, 0.21 % and 0.22 % under 50, 100 and 200 kPa respectively. When the thermal volumetric deformation stabilized, the samples were sheared (0.02 mm/min) at 20 ^{o}C (Figure 11). The shear stress corresponding to 10 % of the sample length in table 5 showed that the temperature cycles have slightly increased the shear strength of the compacted soil under normal stresses of 50 and 100 kPa while it decreased slightly under 200 kPa compared to reference tests at 20 ^{o}C. This shear stress variation as well as the volumetric response of the cyclic tests follows the same trend as the monotonic tests at 50 ^{o}C (Figure 11). In both tests, with increasing the normal stress, the dilative response under lower normal stress (50 and 100 kPa) tends towards a contractive one under higher vertical stress (200 kPa).

The Mohr-Coulomb plane after temperature cycles showed that the cohesion increased by 4 kPa (from 13.0 to 17.4 kPa) and the friction angle remained unchanged compared to the reference test at 20 ^oC (Table 5). The variation of the cohesion was the same as the test at 50 ^oC. If the volumetric deformation due to heating will be one reason for the shear increase, it can be concluded that the first heating has a significant impact on the shearing response.

5 Discussion

5.1 Temperature effect on consolidation parameters

The shrinkage of the elastic domain, generally denoted thermal softening in literature, is generally explained by the temperature-dependent properties of water and changes in the fabric of pores structure (Baldi et al. 1988; Mon et al. 2013). This thermal softening causes the normal consolidation line shifts to the left and consequently the apparent preconsolidation pressure decreases (Tidfors and Sällfors 1989; Shariatmadari and Saeidijam 2012)."

In terms of consolidation behavior, temperature variations had a negligible effect on the compression index (C_c) and swelling index (C_s) of the studied compacted soil but they had an impact on apparent preconsolidation pressure ($\sigma_p^{'}$). The observed results are in accordance with those of other authors on saturated natural and compacted soil samples (François et al. 2007; Kaddouri et al. 2019).

The shrinkage of the elastic domain, generally denoted thermal softening in literature, is generally explained by the temperature-dependent properties of water and changes in the fabric of pores structure (Baldi et al. 1988; Marques et al. (2004); Mon et al. 2013). This thermal softening causes the normal consolidation line shifts to the left and consequently the apparent preconsolidation pressure decreases (Marques et al. 2004; Tidfors and Sällfors 1989; Shariatmadari and Saeidijam 2012).

5.2 Volumetric response due to the temperature cycles

The thermo-elastoplastic volumetric response of the compacted soil due to temperature cycles under different vertical stresses was found to be state-dependent (OC or NC). Whatever the vertical stresses, in the overconsolidated state, the elastic volumetric deformation was induced whereas in normally consolidated states, for both oedometric and shear tests, a significant thermal plastic strain was observed during the first temperature cycle (Figures 8 and 10). After the first cycle, subsequent cycles induced lower thermal plastic strain. In NC state, the sample is subjected to the maximum experienced vertical stress, and simultaneously, the temperature is raised. This modification would lead to a decrease in pore water viscosity, which consequently increases the permeability and facilitates the particle rearrangements. Campanella and Mitchell (1968), Baldi et al. (1988), Di Donna and Laloui (2015); Ng et al. (2019) and Shetty et al. (2019) observed the same type of thermo-plastic strain induced by heating-cooling cycles, in NC clayey and silty clay soils. Some researchers reported that the amount of thermal volumetric change depends on the plasticity index (PI) of the soil (Abuel-Naga et al. 2007; Ghaaowd et al. 2015). The soil with higher plasticity index shows more thermo-plastic deformation (Delage et al. 2000). Di Donna and Laloui (2013) reported a volumetric deformation of 0.6 % for natural silty clay soils with a plasticity index of 18% while, for the studied soil in this paper, the volumetric deformation was 0.15% with a plasticity index of 6.6% .

5.3 Temperature cycles effect on consolidation parameters

The compacted soil in NC state after being subjected to thermal cycles (under 170 and 400 kPa), was reloaded vertically at 20 ^{o}C. After thermal plastic deformation and void ratio decrease, the compacted soil shows less compressibility with subsequent loading (slope of ac is less than the compression index, C_c at 20 ^{o}C, Figure 9b). This behavior can be due to the increase in the stiffness and hardness of the soil caused by thermal cycles. While by subsequent loading the void ratio converged to the void ratio of the reference oedometric test at 20 ^oC (Figure 9b and 9c). This means that the impact of thermal plastic deformation of the compacted soil in NC state disappears upon subsequent

loading. This observation is corroborated with the findings reported by Di Donna and Laloui (2013) and Shetty et al. (2019) who have studied the effect of thermal cycles on the thermal volumetric change of silty clay soil.

5.4 Heating or cooling and temperature cycles effect on shear characteristics

In terms of structural stability of an embankment made of studied compacted soil, the friction angle was not affected by temperature variation which has been confirmed by several studies on other soils in the literature (Hueckel and Baldi 1990; Burghignoli et al. 2000; Ghahremannejad 2003; Cekerevac and Laloui 2004; Maghsoodi et al. 2020). The induced thermal volumetric deformation during heating or temperature cycles slightly increased the cohesion. Cooling decreased the shear stress under higher normal stresses and consequently, the cohesion increased by 7.6 kPa.

In consolidation and shear behavior, two different behavior was observed. Regarding the consolidation behavior, on one hand, the heated compacted soil showed a softening behavior, on the other hand, the shear stress slightly increased. The increase in cohesion can be related to the thermal volumetric contraction that occurred in the heating phase which densified the samples. At lower temperature (5 ^oC) oedometric tests showed lower settlement during the consolidation phase, while, the shear test results showed that the compacted soil under high normal stress has low shear strength. This trend needs to be confirmed with triaxial tests or other tests under higher stress. This could be explained by the fact that the links between soil particles in low temperatures at the microstructural level could become more fragile and consequently the strength could decrease. Further investigations on the microstructure of heated and cooled specimens are necessary to confirm this explanation.

Regarding the volumetric response during shearing, the dilatation is the result of two different events: (i) rolling and sliding of soil particles (ii) normal stress-induced contraction. The soil particle rearrangements caused a disturbance and result in a volume augmentation, whereas the contraction process decreases the soil volume. When the normal stress is relatively small, the soil particle rolling and the subsequent disorder are

dominant. In high normal stresses, the contraction becomes more dominant and the particle rearrangement is confined (Yavari et al. 2016; Zhao et al. 2017; Kouakou et al. 2020). Therefore, the dilatation decreases with normal stress increase.

5.5 Engineering implications of results

Based on thermo-mechanical paths in this study, it can be confirmed that in the construction phase the horizontal heat exchanger loops can be placed in different depths in an embankment. The experimental results showed that the temperature variations, either monotonic (heating or cooling) or temperature cycles tend towards conservation or even improvement of bearing capacity and embankment slopes stability. In terms of consolidation behavior in thermal charging and discharging seasons, when the compacted soil is exposed to monotonic temperature variations, due to the very small differences in compression index at different temperatures, the effect of temperature on the embankment global settlement can be considered negligible. Furthermore, the volumetric response under different vertical stresses (50 to 200 kPa) at different embankment depths (2.5 to 10 m) due to heating and temperature cycles could be also small enough to be neglected.

Thus, it can be concluded that the effect of temperature on the global mechanical behavior of the studied compacted soil with temperature variation range from 5 to 50 ^oC could be negligible. It should be noted that the embankment is in interaction with the atmosphere from its top and lateral surfaces, the thermal efficiency of the structure could be affected due to the heat losses. Consequently, it is better to place the heat exchangers far from the top and lateral surfaces. The tests in this study were performed on compacted soil at an initial optimal compaction state for thermal properties (w=16.3 and $\rho_d = 1.79 Mg.m^{-3}$). This initial soil condition could affect thermo-hydro-mechanical responses to the temperature variation. Therefore, the initial soil compaction state should take into account the optimal thermal soil properties.

6 Conclusions

This study investigated the consolidation and shear behavior of compacted sandy lean clay subjected to the monotonic and cyclic temperature variations. This type of soil is frequently used for embankment application in France. It should be noted that these tests were performed in the saturated state which underestimates soil mechanical properties. The temperature-controlled oedometric and direct-shear devices were used to perform non-isothermal tests.

Based on the results of the oedometric test, the following conclusions can be drawn:

• the heated compacted soil shows a softening behavior, in contrast, cooled compacted soil shows hardening behavior;

• the compression index and swelling index were unchanged with temperature variation;

• the apparent preconsolidation pressure decreased with heating and increased with cooling;

• the volumetric response of compacted soil depends on the stress history. In an overconsolidated state, a reversible deformation was observed, and in a normally consolidated state the temperature cycles induced a thermal plastic contraction;

• the compacted soil subjected to temperature cycles showed a hardening behavior.

The results of direct shear tests showed that heating from 20 to 50 ^oC and temperature cycles had a negligible effect on shear characteristics whereas cooling from 20 to 5 ^oC decreased the shear stress at higher normal stresses (200 kPa).

These results are essential in designing the energy geostructures in a similar range of temperatures. Further work should be performed to investigate the microstructural behavior of studied soil due to heating or cooling. Moreover, in terms of thermal efficiency behavior, a numerical simulation will be performed to investigate the suitable position of horizontal heat exchanger loops due to the heat loss caused by soil-atmospheric interaction.

References

Abedin, A. and Rosen, M., 2011. A critical review of thermochemical energy storage systems, *The open renewable energy journal* **4**(1).

Abuel-Naga, H., Bergado, D., Bouazza, A. and Ramana, G., 2007. Volume change behaviour of saturated clays under drained heating conditions: experimental results and constitutive modeling, *Canadian Geotechnical Journal* **44**(8): 942–956.

Abuel-Naga, H., Bergado, D., Soralump, S. and Rujivipat, P., 2005. Thermal consolidation of soft bangkok clay, *Lowland Technology International Journal* **7**(1): 13–22.

AFNOR, P., 1993. 94–051. soil: investigation and testing–determination of atterberg's limits–liquid limit test using casagrande apparatus-plastic limit test on rolled thread, *Association Française de Normalisation* .

ASTM, D., 1994. 3080-90: Standard test method for direct shear test of soils under consolidated drained conditions, *Annual book of ASTM standards* **4**: 290–295.

ASTM, D., 2011. Standard test methods for one-dimensional consolidation properties of soils using incremental loading.

ASTM, E., 2000. 2089-00. standard practices for ground laboratory atomic oxygen interaction evaluation of materials for space applications, *Annual book of ASTM standards* .

Baldi, G., Hueckel, T. and Pellegrini, R., 1988. Thermal volume changes of the mineral–water system in low-porosity clay soils, *Canadian geotechnical journal* **25**(4): 807–825.

Beier, R. A. and Holloway, W. A., 2015. Changes in the thermal performance of horizontal boreholes with time, *Applied Thermal Engineering* **78**: 1–8.

Boukelia, A., 2016. *Modélisations physique et numérique des géostructures énergétiques*, PhD thesis, Université de Lorraine.

Burghignoli, A., Desideri, A. and Miliziano, S., 2000. A laboratory study on the thermomechanical behaviour of clayey soils, *Canadian Geotechnical Journal* **37**(4): 764–780.

Campanella, R. G. and Mitchell, J. K., 1968. Influence of temperature variations on soil behavior, *Journal of Soil Mechanics & Foundations Div* .

Casagrande, A., 1936. The determination of pre-consolidation load and it's practical significance, *Proc. Int. Conf. Soil Mech. Found. Eng. Cambridge, Mass., 1936*, Vol. 3, p. 60.

Cekerevac, C. and Laloui, L., 2004. Experimental study of thermal effects on the mechanical behaviour of a clay, *International journal for numerical and analytical methods in geomechanics* **28**(3): 209–228.

Delage, P., Sultan, N. and Cui, Y. J., 2000. On the thermal consolidation of boom clay, *Canadian Geotechnical Journal* **37**(2): 343–354.

Delage, P., Sultan, N., Cui, Y.-J. and Ling, L. X., 2009. Permeability changes in boom clay with temperature, *International Conference and Workshop" Impact of Thermo-Hydro-Mechanical-Chemical (THMC) processes on the safety of underground radioactive waste repositories", European Union, Luxembourg, 29 September-1 October 2009*.

Di Donna, A., 2014. *Thermo-mechanical aspects of energy piles*, PhD thesis.

Di Donna, A. and Laloui, L., 2013. Soil response under thermomechanical conditions imposed by energy geostructures, *Energy Geostructures: Innovation in Underground Engineering* pp. 3–21.

Di Donna, A. and Laloui, L., 2015. Response of soil subjected to thermal cyclic loading: experimental and constitutive study, *Engineering Geology* **190**: 65–76.

Eriksson, L., 1989. Temperature effects on consolidation properties of sulphide clays, *International Conference on Soil Mechanics and Foundation Engineering: 13/08/1989-18/08/1989*, Balkema Publishers, AA/Taylor & Francis The Netherlands, pp. 2087–2090.

François, B., Salager, S., El Youssoufi, M., Ubals Picanyol, D., Laloui, L. and Saix, C., 2007. Compression tests on a sandy silt at different suction and temperature levels, *Computer applications in geotechnical engineering*, pp. 1–10.

Gan, G., 2013. Dynamic thermal modelling of horizontal ground-source heat pumps, *International Journal of Low-Carbon Technologies* **8**(2): 95–105.

Ghaaowd, I., Takai, A., Katsumi, T. and McCartney, J. S., 2015. Pore water pressure prediction for undrained heating of soils, *Environmental Geotechnics* **4**(2): 70–78.

Ghahremannejad, B., 2003. Thermo-mechanical behaviour of two reconstituted clays.

Hesaraki, A., Holmberg, S. and Haghighat, F., 2015. Seasonal thermal energy storage with heat pumps and low temperatures in building projects—a comparative review, *Renewable and Sustainable Energy Reviews* **43**: 1199–1213.

Hillel, D., 1980. Fundamentals of soil physics academic, *San Diego, CA* .

Hueckel, T. and Baldi, G., 1990. Thermoplasticity of saturated clays: experimental constitutive study, *Journal of geotechnical engineering* **116**(12): 1778–1796.

Iverson, R. M. and Major, J. J., 1987. Rainfall, ground-water flow, and seasonal movement at minor creek landslide, northwestern california: Physical interpretation of empirical relations, *Geological Society of America Bulletin* **99**(4): 579–594.

Jradi, M., Veje, C. and Jørgensen, B., 2017. Performance analysis of a soil-based thermal energy storage system using solar-driven air-source heat pump for danish buildings sector, *Applied Thermal Engineering* **114**: 360–373.

Kaddouri, Z., Cuisinier, O. and Masrouri, F., 2019. Influence of effective stress and temperature on the creep behavior of a saturated compacted clayey soil, *Geomechanics for Energy and the Environment* **17**: 106–114.

Kouakou, N., Cuisinier, O. and Masrouri, F., 2020. Estimation of the shear strength of coarse-grained soils with fine particles, *Transportation Geotechnics* **25**: 100407.

Lahoori, M., Jannot, Y., Rosin-Paumier, S., Boukelia, A. and Masrouri, F., 2020. Measurement of the thermal properties of unsaturated compacted soil by the transfer function estimation method, *Applied Thermal Engineering* **167**: 114795.

671 Lahoori, M., Rosin-Paumier, S., Stoltz, G. and Jannot, Y., 2020. Thermal conductivity
672 of nonwoven needle-punched geotextiles: effect of stress and moisture, *Geosynthetics*
673 *International* pp. 1–9.

674 Li, Y., Dijkstra, J. and Karstunen, M., 2018. Thermomechanical creep in sensitive clays,
675 *Journal of Geotechnical and Geoenvironmental Engineering* **144**(11): 04018085.

676 Li, Y., Xu, W., Wang, S., Wang, H. and Dai, Y., 2019. Slope stability analysis with
677 reference to rainfall infiltration in the yongping copper mine, china., *Current Science*
678 *(00113891)* **116**(4).

679 Liu, J., Yang, C., Gan, J., Liu, Y., Wei, L. and Xie, Q., 2017. Stability analysis of
680 road embankment slope subjected to rainfall considering runoff-unsaturated seepage and
681 unsaturated fluid–solid coupling, *International Journal of Civil Engineering* **15**(6): 865–
682 876.

683 Ma, Q., Ng, C., Mašín, D. and Zhou, C., 2017. An approach for modelling volume
684 change of fine-grained soil subjected to thermal cycles, *Canadian Geotechnical Journal*
685 **54**(6): 896–901.

686 Maghsoodi, S., Cuisinier, O. and Masrouri, F., 2020. Thermal effects on mechanical
687 behaviour of soil–structure interface, *Canadian geotechnical journal* **57**(1): 32–47.

688 Marques, M. E. S., Leroueil, S. and Soares de Almeida, M. d. S., 2004. Viscous behaviour
689 of st-roch-de-l'achigan clay, quebec, *Canadian Geotechnical Journal* **41**(1): 25–38.

690 Mon, E. E., Hamamoto, S., Kawamoto, K., Komatsu, T. and Moldrup, P., 2013. Tem-
691 perature effects on geotechnical properties of kaolin clay: simultaneous measurements
692 of consolidation characteristics, shear stiffness, and permeability using a modified oe-
693 dometer, *GSTF International Journal of Geological Sciences (JGS)* **1**(1).

694 Morin, R. and Silva, A. J., 1984. The effects of high pressure and high temperature on
695 some physical properties of ocean sediments, *Journal of Geophysical Research: Solid*
696 *Earth* **89**(B1): 511–526.

697 Moritz, L., 1995. *Geotechnical properties of clay at elevated temperatures*, Vol. 47, Swedish
698 Geotechnical Institute Linköping, Sweden.

699 Ng, C. W. W., Mu, Q. and Zhou, C., 2019. Effects of specimen preparation method on
700 the volume change of clay under cyclic thermal loads, *Géotechnique* **69**(2): 146–150.

701 Ng, C. W. W. and Zhou, C., 2014. Cyclic behaviour of an unsaturated silt at various
702 suctions and temperatures, *Géotechnique* **64**(9): 709–720.

703 Rahardjo, H., Li, X., Toll, D. G. and Leong, E. C., 2001. The effect of antecedent rainfall
704 on slope stability, *Unsaturated Soil Concepts and Their Application in Geotechnical*
705 *Practice*, Springer, pp. 371–399.

706 Shariatmadari, N. and Saeidijam, S., 2012. The effect of thermal history on thermo-
707 mechanical behavior of bentonite-sand mixture, *International Journal of Civil Engi-*
708 *neering* **10**(2): 162–167.

709 Shetty, R., Singh, D. and Ferrari, A., 2019. Volume change characteristics of fine-grained
710 soils due to sequential thermo-mechanical stresses, *Engineering Geology* **253**: 47–54.

711 Stojanović, B. and Akander, J., 2010. Build-up and long-term performance test of a
712 full-scale solar-assisted heat pump system for residential heating in nordic climatic con-
713 ditions, *Applied Thermal Engineering* **30**(2-3): 188–195.

714 Thibbotuwawa, D. and Weerasekera, K., 2013. Study of stabilization of unstable area
715 and development of mitigation measures for landslide at peradeniya, due to widening
716 of town roads, *ENGINEER* **46**(02): 43–57.

717 Tidfors, M. and Sällfors, G., 1989. Temperature effect on preconsolidation pressure.

718 Uchaipichat, A. and Khalili, N., 2009. Experimental investigation of thermo-hydro-
719 mechanical behaviour of an unsaturated silt, *Géotechnique* **59**(4): 339–353.

720 Yavari, N., 2014. *Aspects géotechniques des pieux de fondation énergétiques*, PhD thesis,
721 Paris Est.

722 Yavari, N., Tang, A. M., Pereira, J.-M. and Hassen, G., 2016. Effect of temperature on the
723 shear strength of soils and the soil–structure interface, *Canadian Geotechnical Journal*
724 **53**(7): 1186–1194.

725 Yazdani, S., Helwany, S. and Olgun, G., 2019. Influence of temperature on soil–pile
726 interface shear strength, *Geomechanics for Energy and the Environment* **18**: 69–78.

727 Zhao, L., Yang, P., Zhang, L.-C. and Wang, J., 2017. Cyclic direct shear behaviors of
728 an artificial frozen soil-structure interface under constant normal stress and sub-zero
729 temperature, *Cold Regions Science and Technology* **133**: 70–81.

List of symbols

- $\sigma_v^{'}$ (kPa) Effective vertical stress
- τ (kPa) Shear stress
- $\sigma_n^{'}$ (kPa) Effective normal stress
- $\sigma_p^{'}$ (kPa) Preconsolidation pressure
- φ $(^o)$ Friction angle of soil
- C_c $(-)$ Compression index
- C_s $(-)$ Swelling index
- c (kPa) Cohesion
- T (^oC) Temperature
- w $(\%)$ water content
- ρ_d (Mg/m^3) Dry density
- e $(-)$ void ratio
- ε_v $(\%)$ Volumetric deformation
- k (m/s) Hydraulic conductivity
- K (m^2) Intrinsic permeability
- μ $(Pa.s)$ Water viscosity
- C_v $(m^2.s^{-1})$ Coefficient of consolidation
- m_v (kPa^{-1}) Coefficient of volume compressibility
- γ_w $(kN.m^{-3})$ unit weight of water
- OCR Overconsolidated ratio
- NC Normally consolidated state
- OC Overconsolidated state