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Impact of temperature variation on pressuremeter test parameters in compacted soils

A. Boukelia & H. Eslami
LEMTA (CNRS, UMR 7563), Université de Lorraine, Vandœuvre-lès-Nancy-France
ESITC de Metz, Metz-France

S. Rosin-Paumier & F. Masrouri
LEMTA (CNRS, UMR 7563), Université de Lorraine, Vandœuvre-lès-Nancy-France

ABSTRACT: In geotechnical engineering, the proper design of thermo-active geostructures (piles, foundations, etc.) and deep waste storage disposals requires a better understanding of the thermo-hydro-mechanical behaviour of natural and compacted soils. For design purposes, important mechanical parameters of the soils such as the pressuremeter modulus (E_P), limit pressure (P_l) and creep pressure (P_f) are usually obtained by pressuremeter in-situ tests. In the present study, pressuremeter tests were conducted in laboratory, using a mini-pressuremeter, to characterise compacted soils. The objective was to examine and quantify the influence of temperature changes on pressuremeter parameters of two different compacted soils: a clay and a loam. These soils were compacted at their optimal water content and 90% of their maximal dry density (standard Proctor) in a thermo-regulated metric scale container of 800 mm in height and 600 mm in diameter. The compacted soils were then subjected to a range of temperatures from 20 to 50 °C.
Only six tests were performed in each container to prevent edge effects and interaction between the tests. The thermal cycles were applied to the soil massif as following: A heating-cooling cycle (20-40-20 °C) for the clay; three heating-cooling cycles (20-50 °C) for the loam. Pressuremeter tests were conducted at the end of several temperature steps. The obtained results showed a decrease in P_l and P_f with increasing temperature for both tested soils, while the variation of E_P was less significant. Through the temperature range tested, a quasi-reversibility of the effect of a heating cycle is obtained.

1 INTRODUCTION

In geotechnical engineering the effect of temperature has to be studied particularly for applications such as the storage of nuclear waste (Rutqvist et al. 2002), the burying of high-voltage cables (De Lieto Vollaro et al. 2011) and the thermo-active geostructures (Pahud 2002). These thermo-active geostructures are used to provide sustainable heating and cooling by thermal exchange between buildings and the ground through liquids that flow through closed-loop circulation systems integrated into the geostructures. Thermo-active geostructures may be piles, diaphragm walls, tunnel linings, basement slabs or walls (Brandl, 2006; Fromentin et al., 1999; Laloui et al., 2003). The classical way in which they are used results in temperature cyclic changes in the surrounding ground temperature. Consequently, there are important questions about the effect of temperature variations on hydro-mechanical soil properties which may affect long-term structure performance. In particular, the contraction of the elastic domain (i.e., the yield locus) with increasing temperature has been demonstrated for various clay materials on centimetric samples (Tanaka et al., 1997; Graham et al., 2001; Cekerevac and Laloui 2004; Marques, 2004; Uchaipichat and Khalili 2009). In this study, tests on larger samples of contrasted materials are performed.

The pressuremeter test is currently used to calculate the bearing capacity of deep foundations (AFNOR, 2000; Standard ASTM, 1999). This test consists in introducing in the soil a cylindrical probe with a flexible cover membrane which can expand radially in a hole. As the soil has a pseudo-elastic reaction versus the probe pressure during a part of the test, it is possible to calculate a pressuremeter modulus E_P. After that, at higher pressures, large displacements take place and the soil becomes plastic. The creep pressure, P_f is defined as the yielding pressure between the pseudo-elastic and plastic behavior. This parameter is directly correlated to the yield locus. As a result it should be possible to quantify the potential contraction of the elastic domain using pressuremeter tests. Thus, we developed an experimental method to carry out mini-pressuremeter tests on homogeneous soils compacted at a controlled density and water content and subjected to monotonic and cyclic thermal variations (Eslami, 2014).

In the following sections, the material and the developed experimental device are first described. Then, the results are detailed and the impact of thermal variations on the pressuremeter parameters is discussed.

2 MATERIAL AND METHOD

In this part, first the studied material is presented, then experimental device is described and finally the mini-pressuremeter tests are detailed.

2.1 *Basic characterization of materials*

The tested materials were an illitic soil and a loam taken in the Paris region (Plaisir). The soils were first dried, pulverized and sieved through 2mm sieve before quartering and then used for various experimentations. The illitic material contains 77% illite, 10% kaolinite, 12% calcite and traces of quartz and feldspar. The Plaisir loam contains 81% quartz, 7% dolomite, 5% calcite, 5% clay materials and 3% felspar.

The particle-size distribution of the illitic soil was determined using a laser Malvern Mastersizer 2000® device (AFNOR, 2009) whereas the particle size distribution of the Plaisir loam was determined using sieving and sedimentometric method. Almost 85% of the particles of the illitic material are smaller than 0.002 mm (clay particles). The Plaisir loam is coarser as only 20% of the particles are smaller than 0.002 mm.

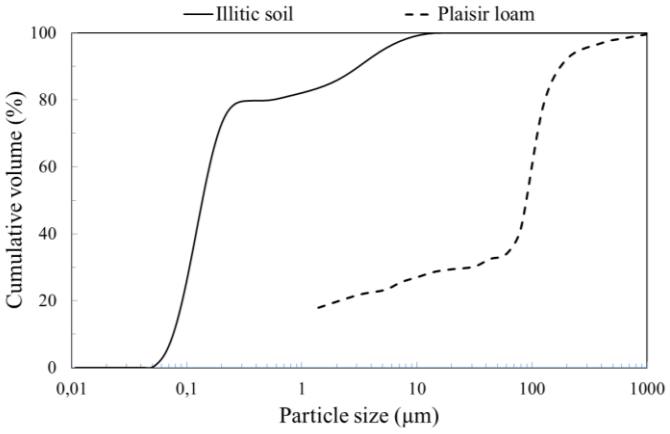


Figure 1. Granulometric curves of the studied materials.

Other basic parameters like liquid limit (LL), plastic limit (PL), plasticity index (PI) (AFNOR, 1993) and specific surfaces (AFNOR, 1999a) were compiled in Table 1.

Table 1 : Basic characterization of studied materials

Material	PL %	LL %	PI	MBV g/100g	w_{OPN} %	ρ_{dmax} Mg/m^3
Illitic soil	34	65	31	5.41	31	1.43
Plaisir loam	21	27	6	1.85	16	1.81

The optimum water contents (w_{OPN}) and maximum dry densities (ρ_{dmax}) were obtained from the standard Proctor curves performed for each material (AFNOR, 1999b) (Figure 2). For the same compaction energy, the maximum dry density reached with the Plaisir loam is significantly higher than with the illitic soil in accordance with its coarser granulometry and its mineralogical content.

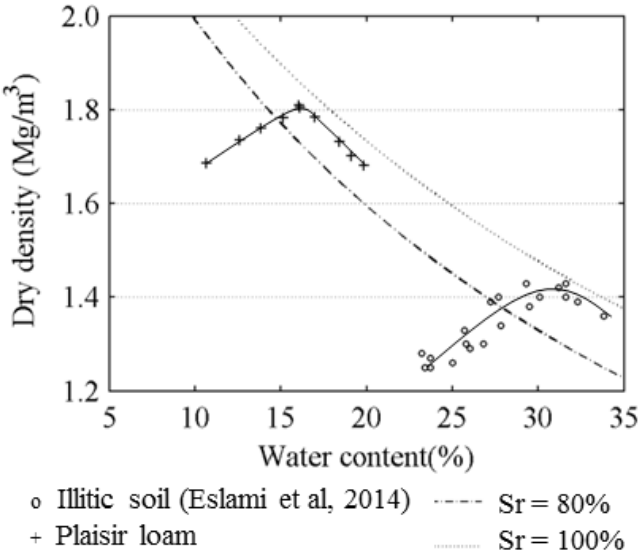


Figure 2: Compaction curves of the studied materials.

The illitic soil is classified as A3 in the French standard for soil classification (GTR, 2000) and as a fat clay, MH, according to the Unified Soil Classification System (Standard ASTM, 2006). The Plaisir loam is classified as A1 in the French standard for soil classification and as a sandy lean clay, CL, according to the Unified Soil Classification System.

2.2 *Experimental device and methods*

To perform mini-pressuremeter tests at controlled temperatures, an homogeneous massif with a large volume is required as well as an experimental device to impose thermal variations to the massif. In this part, the developed methodology to obtain a meter-scale sample with homogeneous properties (temperature, water content and dry densities) is described.

First, the required amount of water was added to the material in a large capacity fixed-speed (38 rpm) mixer (MIX120®) to reach the target water content (Table 2).

Table 2: Characteristics of the prepared samples.

Material	w (%)	ρ_d (Mg/m^3)	*Tmin* (°C)	*Tmax* (°C)	*Nb cycles*
Illitic soil	30.5±0.5	1.31±0.01	20	40	1
Plaisir loam	16.1±0.2	1.72±0.02	20	50	3

The wet material was stored in 8 plastic drums for a minimum of 5 days to ensure good homogenization. A pneumatic compactor was used to compact the material in a cylindrical stainless steel container of 800 mm in height and 600 mm in diameter (Figure 3). The compactor applied dynamic forces on a metallic plate of 4 mm in thick and 600 mm in diameter put on the top of the material to facilitate a homogeneous compaction of the soil. To ensure a homogeneous density of the massif, the compaction was performed in eleven 70-mm-thick layers (Figure 4).

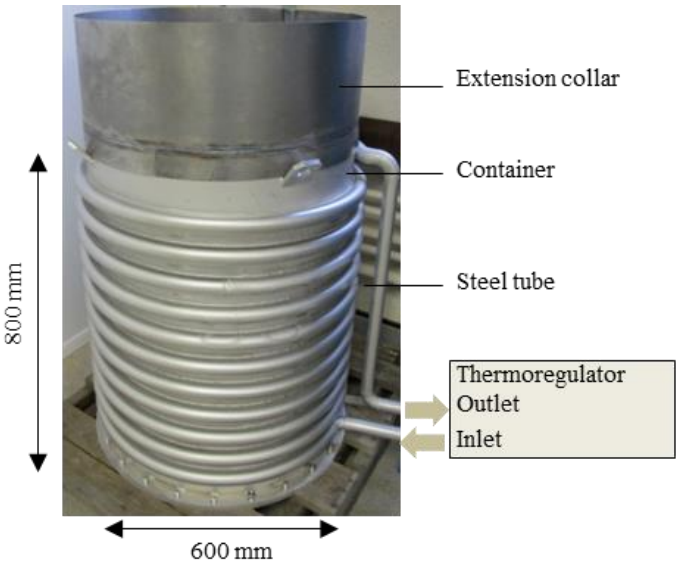


Figure 3: Thermo-regulated metric scale container.

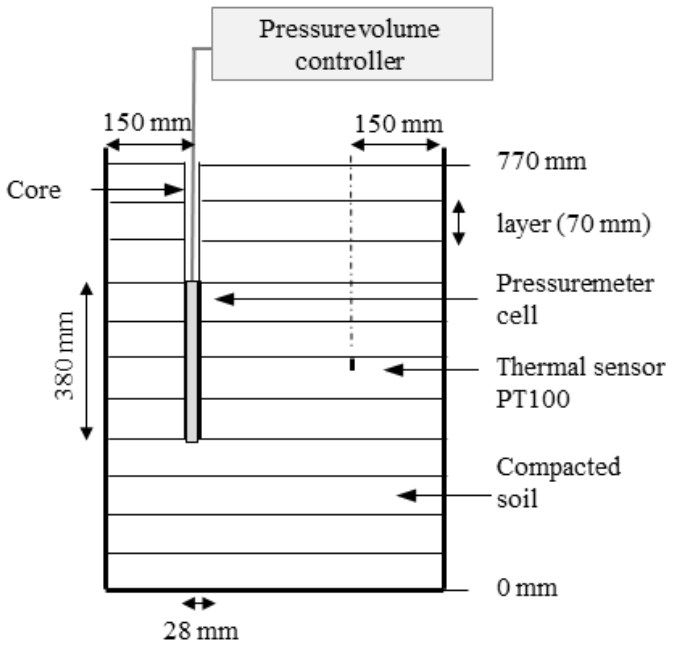


Figure 4: Position of the pressuremeter cell.

A stainless steel tube welded to the outside of the container was connected to a Vulcatherm® thermoregulator to facilitate the circulation of an ethylene glycol-water solution at the target temperature (maximum range: -20 to 90 °C) in the tube (Figure 3). Thus, the soil compacted in the container was heated or cooled by the container's outer lateral surface to a maximal range of temperature from 20 to 50°C (Table 2). Insulating sleeves were placed around the tube to reduce the heat exchange with the surrounding atmosphere. The top of the massif was insulated with a plastic film to preserve the initial water content. Finally, the entire device was placed in a box constructed of 40-mm-thick extruded polystyrene plates to reinforce the insulation.
Seven thermal sensors PT100 were positioned within the massif at various depths and various distances from the wall of the container. The sensors were plugged to a data logger to monitor the temperature variation inside the compacted soil.

2.3 *Mini-pressuremeter tests*

The principle of a pressuremeter test is to introduce a cylindrical probe with a flexible cover membrane which can expand radially in a hole (AFNOR, 2000; ASTM, 1999). The pressuremeter curve consists in 3 steps: (i) the probe inflates to obtain the contact with the wall of the hole, (ii) the volume increases linearly with the increasing pressure allowing the calculation of the pressuremeter modulus E_P (the soil pseudo-elastic reaction against the probe pressure), and (iii) the large displacements take place and the soil becomes plastic (Figure 5). The creep pressure, P_f is the boundary between the second and the third steps of the test. The limit pressure P_l is the measured pressure when the injected volume reaches twice the original volume of the cavity.

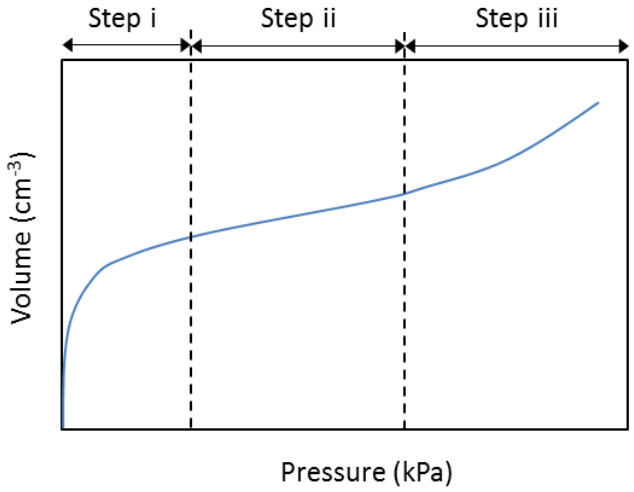


Figure 5 : The 3 steps of a pressuremeter curve

Only six mini-pressuremeter tests were performed in each massif to prevent edge effects and cross-influence between the tests. The test points were positioned on a concentric circle with a diameter half than that of the container. All the test points were located at the same radial position for a correct comparison of the results.
The pressuremeter tests were conducted with an APAGEO® mini-pressuremeter probe of 380 mm in height and 28 mm in diameter. Before each pressuremeter test, a core with a diameter equal to that of the mini-pressuremeter probe was extracted using a

core sampler. The 630-mm-length core was divided into small pieces to measure the water content and density of the material as a function of depth. The center of the probe was positioned halfway along the height of the compacted soil (385 mm). The probe was connected to a GDS® pressure-volume controller. The pressure controlled test consisted in applying increasing pressure with equal increments of 25kPa for at least one minute per step. The equilibrium volume was measured for each increment and the volume was plotted as a function of pressure. The test was stopped when the injected volume (i.e., the volume variation limit of the probe) reached 140,000 mm^3. Immediately after the pressuremeter test at a given temperature, the borehole was filled with the same material, at the same water content, to avoid influencing the later tests. The effect of temperature variations on the resistance of the mini-pressuremeter membrane was measured by placing the probe in a climatic chamber at a given temperature during the calibration test of the membrane resistance.

3 RESULTS

The results of the pressuremeter tests performed on the illitic soil and the Plaisir loam are successively presented in this part.

3.1 *Illitic soil*

For the first test series, starting from 20 °C, the soil was heated up to 40 °C and then cooled down to 20 °C. Figure 6 shows the temperature variation as recorded by a thermal sensor placed at 150 mm from the edge of the massif and at the middle of its height. The thermal equilibrium was reached after 65h within the limit of ±1 °C.

The water content (w) was maintained unchanged all test long. To verify this point, the average water content of the soil close to the test area (from 200 to 580 mm in depth) was measured (Table 3). At 40 °C, (w) was slightly lower than at 20 °C. This might be due to the evaporation of water during the core drilling and the sample weighting as the (w) values measured at the end of the test (I20c,d) were identical to the (w) at the beginning of the test (I20b). The average dry densities were almost identical, confirming the homogeneity of the massif.

Two mini-pressuremeter tests were performed at each temperature step: I20a, I20b, then I40a, I40b and finally I20c, I20d. The test I20a failed due to a membrane leakage. The results of the five other tests are presented in Figure 7.

The evaluation of the pressuremeter parameters (E_p, P_l and P_f), allowed the quantitative comparison of the tests at different temperatures (Table 3, Figure 8). The values of P_l and P_f decreased significantly when the massif was heated up to 40 °C. Thus, the soil was yielded under lower pressures at 40 °C than at 20 °C. In other words, the results showed a softening of the soil with heating.

The pressuremeter parameters for I20b and I20c-d tests were close that showed a good reversibility of the effect of the temperature variation in the range of 20-40 °C. The softening due to the heating and the reversibility of the observed effects on the creep pressure and the pressure limit were also noticed on the pressuremeter modulus (*Ep*) to a lower extent.

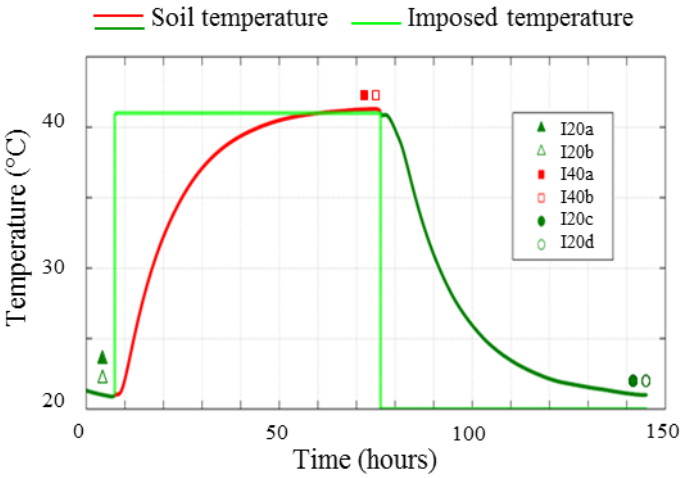


Figure 6: Temperature variation in the illitic compacted soil at 150 mm from the edge of the container and the chronology of the tests: heating-cooling cycle (20-40-20 °C), time of the pressuremeter tests (I20a, b, c, d, I40a, b).

Table 3: Pressuremeter parameters for the test performed on illitic samples: heating cycle (20-40-20 °C).

Test	T (°C)	Cycle	w (%)	ρ_d ($Mg.m^{-3}$)	P_f (kPa)	P_l (kPa)	E_p (MPa)
I20b	20	0	31.0	1.31	194	355	3.54
I40a	40	1	30.1	1.31	166	321	4.16
I40b	40	1	30.4	1.31	165	288	3.25
I20c	20	1	31.1	1.31	197	379	4.54
I20d	20	1	31.1	1.32	178	352	3.89

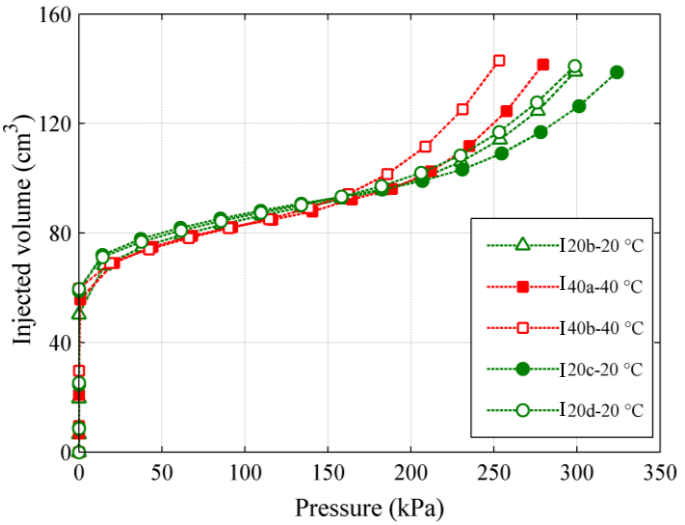


Figure 7: Pressuremeter curves for the tests on illitic material: I20b, I40a-b and I20c-d.

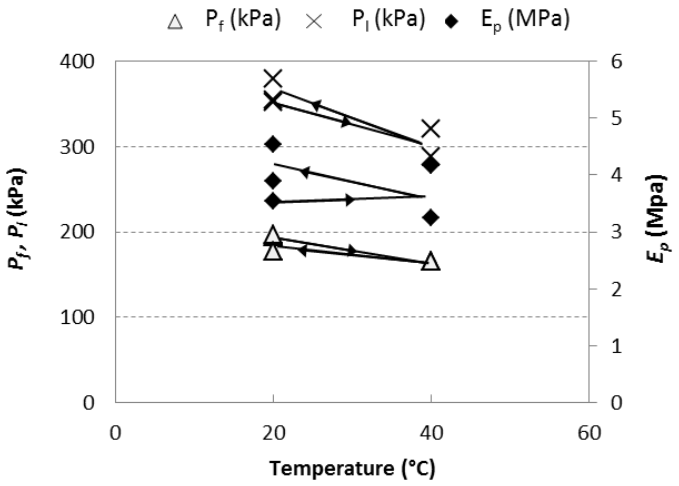


Figure 8 : Impact of temperature variation on pressuremeter test parameters in illitic compacted soil.

3.2 *Loam tests*

For the second test series, the test began 6 days after the compaction of the massif to ensure a good homogeneity of the moisture in the entire sample. The initial temperature of the loam compacted soil was 20 °C, the soil was submitted to three heating cycles up to 50 °C and then cooling down to 20 °C. Figure 9 shows the imposed temperature on the outer lateral surface of the container and the temperature variation as recorded by a sensor placed at 150 mm from the edge of the massif and at the middle of its height. The thermal equilibrium was reached after 30h within the limits of ±1 °C. Each step lasted 30 to 60 h. An electric failure caused a detectable decreasing of the temperature during the first heating step. The I20a-b tests were performed after the achievement of the previously set temperature.

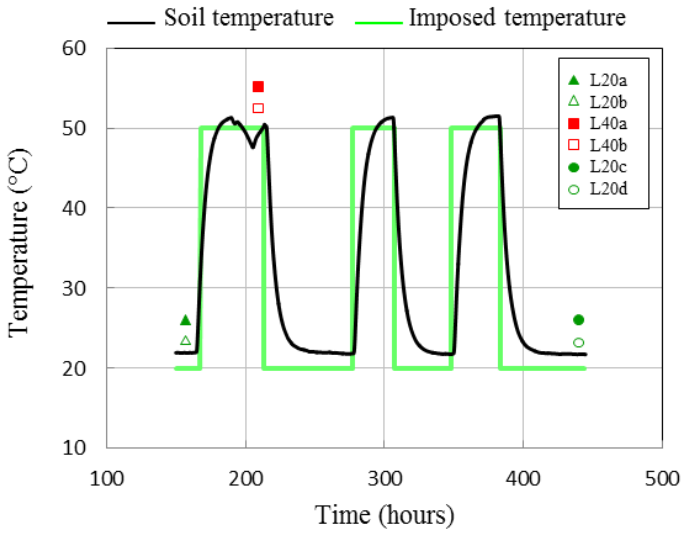


Figure 9: Temperature variation in the loam at 150 mm from the edge of the container and the chronology of the tests: 3 heating-cooling cycles (20-50-20 °C) and time of the pressuremeter tests.

The average water content of the soil close to the test area (from 200 to 580 mm in depth) was measured (Table 4). At 50 °C, as presented for the 1st test series, (w) was slightly lower than at 20 °C. The average dry densities were identical, confirming the homogeneity of this parameter over the massif.

Two mini-pressuremeter tests were performed at several temperature steps: L20a and L20b before the first cycle; L50a and L50b at the end of the first heating cycle and finally L20c and L20d at the end of the test after the application of the 3rd cycle. The results of these six tests are presented in Figure 10.

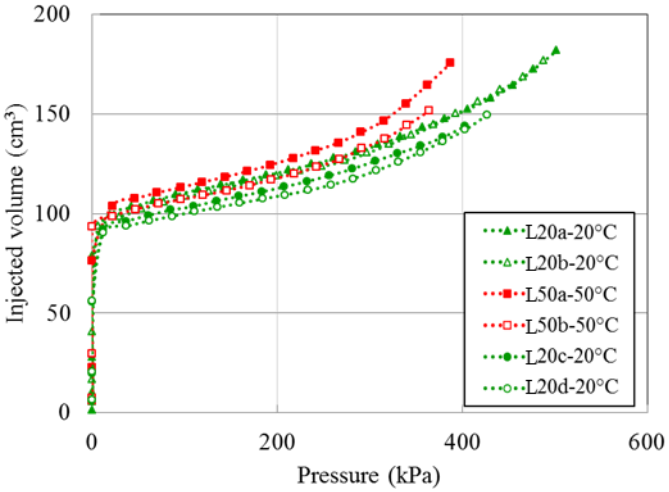


Figure 10: Pressuremeter curves for the tests on loam material: heating-cooling cycle (20-50 °C).

The evaluation of the pressuremeter parameters (E_p, P_l and P_f), allowed the quantitative comparison of the tests at different temperatures (Table 4, Figure 11). The values of the three pressuremeter parameters decreased significantly when the massif was heated up to 50 °C. As observed for the illitic compacted soil, the results showed a softening of the loam soil with heating. At the end of the cycles, at 20 °C, the pressuremeter parameters returned back to their initial values: results of L20c-d tests were close to those of L20a-b. A reversibility of the effect of the temperature variation in the range of 20-50 °C was noticed for this material as for the illitic soil.

Table 4: Pressuremeter parameters for the test performed on loam samples: 3 heating cycles (20-50-20 °C).

Test	T (°C)	Cycle	w (%)	ρ_d (Mg.m^{-3})	P_f (kPa)	P_l (kPa)	E_p (MPa)
L20a	20	0	16.2	1.71	278	657	5.39
L20b	20	0	16.2	1.72	280	591	5.18
L50a	50	1	15.9	1.74	220	517	4.90
L50b	50	1	16.0	n.c.	218	480	5.46
L20c	20	3	16.3	1.73	270	648	5.63
L20d	20	3	16.0	1.71	250	535	5.86

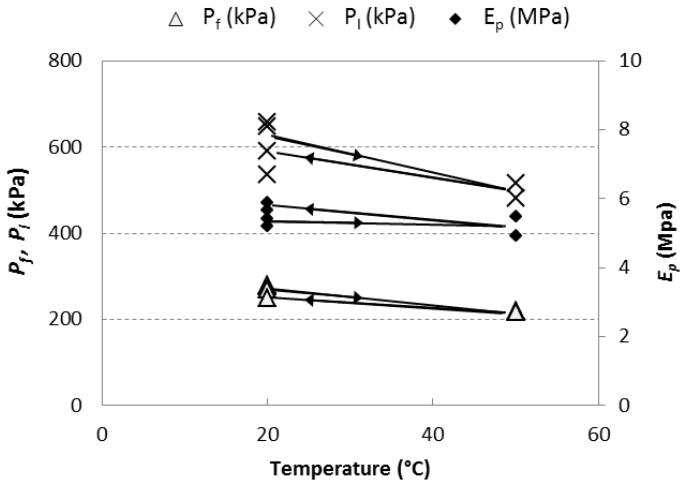


Figure 11 Impact of temperature variation on pressuremeter test parameters in compacted loam.

4 DISCUSSION

In this part, the results obtained on both materials are compared. The pressuremeter parameters measured on the illitic soil are lower than for the Plaisir loam:

- P_f illitic soil = 70 % of P_f Plaisir loam;
- P_l illitic soil = 57 % of P_l Plaisir loam;
- E_p illitic soil = 67 % of E_p Plaisir loam.

To compare the first and the second series of tests, the average values obtained at the end of the first step at 20 °C, P_f (20), P_l (20) and E_p (20) were considered as reference values, and all other values were normalized with respect to these reference values (see equations 1, 2 and 3). Normalized parameters were presented in Table 5.

$$E_{n.p} = \frac{E_p(T)}{\overline{E_p}(20)} \quad (1)$$

$$p_{n.f} = \frac{p_f(T)}{\overline{p_f}(20)} \quad (2)$$

$$p_{n.l} = \frac{p_l(T)}{\overline{p_l}(20)} \quad (3)$$

Figure 12 shows the evolution of the normalized parameters at each step of each test series.

Table 5: Normalized pressuremeter parameters for both series.

Material	T (°C)	*Cycle*	$P_{n.f}$	$P_{n.l}$	$E_{n.p}$
Illite	20	0	1.00	1.00	1.00
Illite	40	1	0.85	0.86	1.05
Illite	20	1	0.97	1.03	1.19
Loam	20	0	1.00	1.00	1.00
Loam	50	1	0.78	0.80	0.98
Loam	20	3	0.93	0.95	1.09

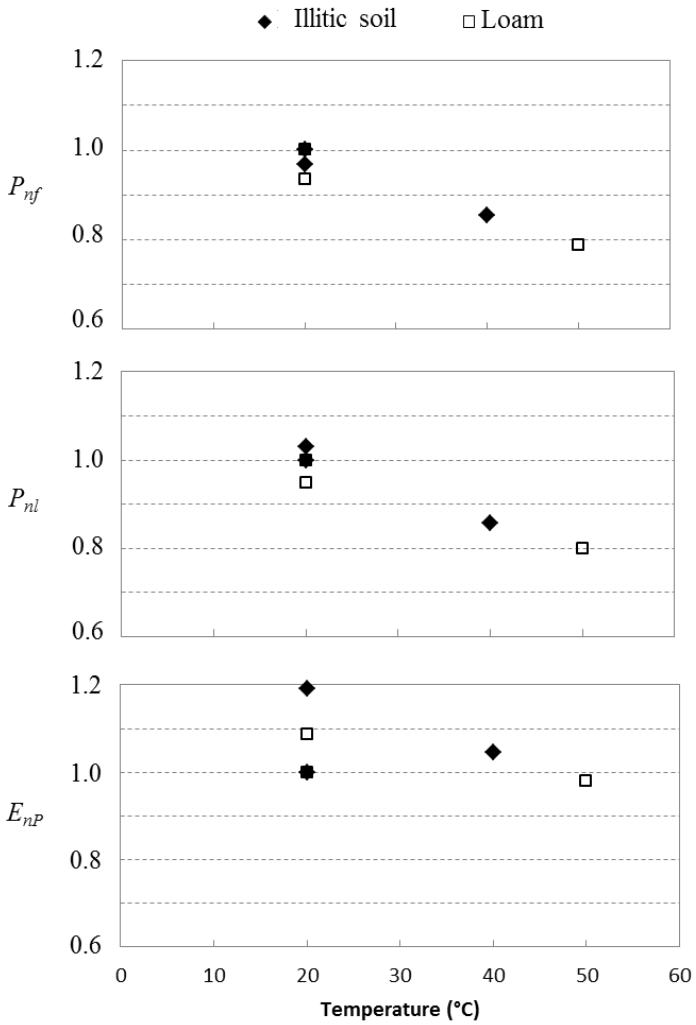


Figure 12: Evolution of the normalized parameters according to the test temperature for two materials.

For the studied materials compacted at 90% of their maximal dry density, the creep pressure and the limit pressure decreased with increasing temperature that evidenced the thermal softening of both materials. These results are consistent with the literature results obtained with oedometric and triaxial tests (Marques et al., 2004, Cekerevac and Laloui, 2004, Graham et al., 2001, Tanaka et al., 1997, Hueckel & Baldi, 1990).

In this study, after heating-cooling cycles, for both soils all pressuremeter parameters recovered approximately their initial values (reversibility of thermal softening). Heating the illitic sample from 20 to 40 °C decreased $P_{n.f}$ by 15% and $P_{n.l}$ by 14%, while returning back to 20 °C increased these parameters respectively up to 12% and 17%. As a similar way, heating the compacted loam from 20 to 50 °C decreased $P_{n.f}$ by 22% and $P_{n.l}$ by 20%, while cooling down to 20 °C increased these parameters up to 15%. The level of $P_{n.l}$ and $P_{n.f}$ measured in the compacted loam at the end of the three thermal cycles was a little lower than the initial values. This trend has to be followed in a future study with more cycles to test a possible cumulative effect.

The comparison between these two materials shows that in spite of their difference in mineralogy, initial water content and dry densities, normalized parameters can be considered as linear. A simple linear regression (equations 4 and 5) may be used to determine P_f and P_l values according to the sample temperature (T):

$$P_f(T) = P_f(20) \times (-0.0072 \times T + 1.1431) \quad (4)$$

$$P_l(T) = P_l(20) \times (-0.0068 \times T + 1.1335) \quad (5)$$

5 CONCLUSIONS

The objective of this paper was to quantify the effect of both monotonic and cyclic temperature variations on different soil pressuremeter parameters. A specific device was developed to measure the mini-pressuremeter parameters in laboratory conditions and at different temperatures. The evolution of the pressuremeter modulus (*Ep*), the creep pressure (P_f) and the limit pressure (P_l) was measured under imposed thermal conditions on a clayey compacted soil and a compacted loam.

The results of the mini-pressuremeter tests on both materials showed a decrease in the creep pressure and the limit pressure with temperature increase (thermal softening), while the variation of the pressuremeter modulus was less significant, this could be due to the well-known higher variability of this parameter. The results tended to show the reversibility of the temperature effects on the measured parameters for one and three heating cycle both for the illitic soil in the tested temperature range (20-40 °C) and the compacted loam in the tested temperature range (20-50 °C).

6 ACKNOWLEDGEMENTS

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