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Effect of temperature and initial state on variation of thermal parameters of fine compacted soils

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1. Introduction

Soil thermal properties are required in some engineering applications such as the design of high-level radioactive waste disposals (Rutqvist, Wu, Tsang, & Bodvarsson, 2002), buried power transmission (De Lieto Vollaro, Fontana, & Vallati, 2011), energy geostructures (Pahud, 2002 and Brandl, 2006) and thermal energy storage (Navarro et al., 2016 and Giordano, Comina, Mandrone, & Cagni, 2016). The study of heat flow in soil is based on the thermal properties and temperature gradient. The thermal parameters governing the transfer of heat are the **thermal conductivity** (λ), which is the ability of the material to conduct heat, the **volumetric heat capacity** (C), which describes the ability of the material to store thermal energy while undergoing a given temperature change, and the **thermal diffusivity** ($\alpha = \lambda/C$), which describes the ability of a material to conduct thermal energy relative to its ability to store thermal energy.

A variety of measurement techniques are available for natural materials with a broad temperature range. Recently, Zhang, Cai,, Liu & Puppala (2016) presented most commonly used measurement techniques such as the steady-state method, the transient hot-wire method, the laser flash diffusivity method and the transient plane source method. The hot-wire method also known as the needle-probe method (ASTM, 2000) is a transient technique that measures temperature rise at a known distance from a linear heat source embedded in the test sample. This method is widely used in natural soil and compacted soil characterization for its accuracy, speed and simple application.

The thermal parameters (λ, C and α) depend on soil parameters such as the mineralogy, water content, bulk density, particle size distribution and structural arrangement (Abu-Hamdeh (2001), Abu-Hamdeh (2003), Tang (2005), Brandl (2006), Ehdezi (2012)). Abu-Hamdeh and Reeder (2000) measured the thermal conductivity of four soils as a function of their water content and density. The authors noted that for each soil, λ increased with increasing density.

Similarly, when the water content increased λ, increased as well. The results of Tang (2005) showed the same trends for a clayey material. Barry-Macaulay, Bouazza, Singh, Wang, and Ranjith (2013) presented the same type of results as part of their important database of Australian natural materials. For instance, as the thermal conductivity of solid particles exceeds those of the air and the water, an increase in the dry density results in an increase in λ. Furthermore, increasing the contact surface between solid particles increases the heat flux and results in an increase of λ. In the same way, as the thermal conductivity of water is higher than that of the air, an increase in the saturation rate results in an increase in λ.

Few studies have been conducted on the thermal conductivity of compacted soils. Ekwue, Stone, and Bhagwat (2006) studied the combined effects of soil density and water content on soil thermal conductivity of three soils: a sandy loam, a clayey loam and a clay. They measured the thermal conductivity for different values of water content and dry density on the compaction curve of these soils. For each soil, λ reaches a maximal value near the Proctor optimum water content. The study of Ekwue et al. (2006) was also focused on the impact of soil mineralogy on λ, and the material with a high sand content showed the most important impact. However, the coupled effect of soil density and water content on the volumetric heat capacity and thermal diffusivity was not well studied. The monotonic and cyclic heat effect on thermal parameters was also not studied.

Several prediction models of soil thermal parameters, taking into account the soil properties, are available to evaluate the thermal conductivity (De Vries (1963), Johansen (1977) and Kersten (1949)). For example, Farouki (1981) and, more recently, Dong, John, McCartney, and Lu (2015) presented an extensive review of the numerous available prediction models. However, these models are perfectible (Dong et al. 2015) and need to be improved to take into account new environmental or industrial issues such as soil temperature.

In civil engineering, the temperature variation range evolves according to the process; for example, cyclic variations from 4 and 30°C were recorded for heat exchange piles (Peron, Knellwolf, & Laloui, 2011) a maximum temperature of 70°C was estimated for thermal energy storage (Giordano et al. 2016), 100°C was used for the design of high-level radioactive waste disposal (Tang, 2005), and 90°C was used in the design of buried power transmission cables (Hanna, Chikhani, & Salama, 1993). Temperature variations affect the physical properties of soil (solid and water particles volumetric variation and change in water status), inducing changes in the thermal properties. Considering the impact of temperature on the thermal proprieties of soils between 0° and 70°C, only a few studies are available. Hiraiwa and Kasubuchi (2000) measured the thermal conductivity of two soils, a clay loam and a light clay, at different volumetric water contents and different temperatures between 5 and 75°C. Their results showed that λ increased with increasing temperature and volumetric water content. Smits, Sakaki, Howington, Peters, and Illangasekare (2013) measured the thermal conductivity and diffusivity of two sands prepared at various saturation rates at different temperatures between 30 and 70°C. Their results showed that the thermal properties increased dramatically for temperatures above 50°C, but small changes in thermal properties were observed at temperatures between 30 and 50°C.

This literature review shows that numerous studies are available on the impact of soil parameters on the soil thermal conductivity; some of these studies address compacted soils, but fewer focus on the compacted soils used in civil engineering that are submitted to cyclic temperature variations from 1 to 70°C. Furthermore, few studies and little data are available on the variation of the volumetric heat capacity and the thermal diffusivity as a function of soil properties, despite their great importance in the study of heat flow and heat storage in soils.

The aim of this study was to better understand the coupled effect of water content (w), dry density (ρ_d) and temperature variations (T) on the thermal parameters (λ, C and α) of compacted soils. The following issues were addressed:

- whether the mineralogy and the size distribution of soil particles affect their thermal properties,
- the coupled effect of w and ρ_d on the thermal parameters, and
- the effect of monotonic and cyclic thermal variation on soil thermal characteristics.

In the following sections, the preparation of the materials and the experimental device are described first. Then, the results are presented and analysed to explain the main evolutions of the thermal properties according to the initial state parameters of compacted soils and the impact of thermal variations.

2. Materials and methods

In this section, the properties of the five studied materials, the compaction of the materials at various water contents and dry densities, and the apparatus used to measure the thermal properties are presented.

2.1. The materials properties

Five different soils were studied. The mineralogical compositions of these soils are presented in *Table 1*. The illitic soil (I) named Arginotech® came from eastern Germany. The Plaisir loam (PL) was extracted from the Paris region and was dried, pulverized and sieved through a 2 mm sieve before being quartered and used for various experiments (Boukelia, 2016). Two other loams from the Parisian basin, namely, the Jossigny loam (JL) and the Xeuilley loam (XL), were also studied. The characteristics of each material including grain size distribution, Atterberg limits (AFNOR, 1993), specific surface (AFNOR, 1999a), carbonate content (AFNOR, 1996) and Proctor compaction parameters (AFNOR, 1999b) are listed in *Table 2*.

115 The particle size distributions were determined using a Laser diffraction particle size analyser
116 (Malvern Mastersizer 2000®) (AFNOR, 2009) for the illitic material (Eslami, Rosin-Paumier,
117 Abdallah, & Masrouri, 2015) and a wetting sieve method for the Plaisir loam. For the
118 Jossigny and Xeuilley loams, the particle size distribution curves were found in the literature
119 (Fleureau & Inderto, 1993 and Blanck, Cuisinier, & Masrouri, 2011). The Proctor optimum
120 water contents (w_{OPN}) and maximum dry densities (ρ_{dmax}) were obtained from the standard
121 Proctor curve performed for each mixture (AFNOR, 1999b) (*Figure 1* and *Table 3*).

122 ***2.2. Sample preparation***

123 Six test series were performed (*Table 5*). In the first series, the effect of the dry density was
124 studied on an illitic soil (I) and a sand-illitic mixture (S+I). In the second series, the effect of
125 water content was studied on the same soils (I and S+I). In the third series, the effect of
126 particle size and mineralogy were evaluated for each soil. Then, the coupled effect of dry
127 density and water content was analysed by measuring the thermal properties of five materials
128 compacted at various water contents and dry densities using constant compaction energy (4^{th}
129 series). Then, the temperature effect was studied on PL, I and S+I by measuring the thermal
130 properties of different points on a compaction curve at varying temperatures within the range
131 of 1 to 70°C (5^{th} series). Finally, the effect of cyclic temperature variations was studied on PL
132 (6^{th} series).

133 To prepare samples at the desired water content and dry density, powdered material was first
134 mixed with water to reach the target water content and then packed into hermitic bags to
135 homogenize over at least 24 h. Two types of samples were prepared. For the 1^{st} and 2^{nd} series,
136 samples 70 mm in height and 35 mm in diameter were statically compacted. For the 3^{rd}
137 through 6^{th} series, samples 116 mm in height and 152 mm in diameter were dynamically
138 compacted in three layers in a CBR (Californian Bearing Ratio) mould. The standard Proctor

compaction energy was applied. The samples were then heated or cooled to different temperatures in a climatic chamber, and the thermal properties of each sample were measured.

2.3. Thermal parameter measurements

The thermal properties were measured using a *KD2 Pro* thermal properties analyser®. Two specific sensors were used: a dual-needle SH-1 and a single needle TR-1. The dual-probe SH-1 consists of two parallel probes (30 mm long and 1.3 mm diameter with 6 mm spacing). One of these probes comprises a thermistor, and the other comprises the heater element. This sensor measures thermal conductivity (λ), thermal resistivity (R), thermal diffusivity (α) and volumetric heat capacity (C) by employing the dual needle heat pulse method. The single needle TR-1 (2.4 mm diameter and 100 mm long) measures only thermal conductivity (λ); this is used when λ is higher than 2 $W.m^{-1}.K^{-1}$. The measurement range and the precision of both sensors are summarized in *Table 5*.

To measure the thermal parameters of sample, the probe was covered by a thin layer of grease (Arctiv Silver® 5 – High-density polysynthetic silver thermal compound) and then was placed in the sample after soil drilling at the same diameter. In this case, the use of the grease is recommended to improve the contact between the sensor needle and the soil. A waiting time of 15 minutes was imposed before each test to reach an equilibrium temperature between the probe and the soil. The presented value is a mean value of 4 tests in different locations of the sample.

3. Experimental results and discussion

In the following sections, the experimental results and discussions for each series are presented successively.

3.1. Dry density effect on thermal parameters (1st series)

The effects of dry density on thermal parameters are studied on both illitic material (I) and a sand-illitic mixture (S+I). Illitic samples were prepared at an initial water content in the range of 28.8 to 33.4% and dry densities varying from 1.20 to 1.52 Mg/m^3. Sand-illitic (S+I) samples were prepared at an initial water content (w) in the range of 16.9 to 20.4% and dry densities (ρ_d) varying from 1.54 to 1.79 Mg/m^3. The variations of water content and dry density were chosen in the same range of the standard Proctor curve for both materials. The samples were thus prepared at water contents and dry densities compatible with their use in geotechnical engineering. The real density (ρ_h) of the samples can be determined from Eq. 1.

$$\rho_h = (1+w) \times \rho_d \quad \text{(Eq. 1)}$$

The results (*Figure 2*a, b, c) showed that the thermal conductivity, volumetric heat capacity and thermal diffusivity increased with increasing dry density for both materials regardless of the water content. Linear increases in λ, C and α as functions of increasing dry density were shown, in agreement with literature.

The thermal diffusivities ($\alpha=\lambda/C$) measured on the illitic samples were significantly lower than those of the sand-illitic samples.

3.2. Water content effect on thermal properties (2nd series)

The effect of water content on the thermal proprieties was showed by Tang (2005), Brandl (2006) and Barry-Macaulay et al. (2013). In *Figure 2*, the range variations of water content and dry density of I and S+I samples were the same as those in part 3.1. The enhancement of thermal conductivity as a function of water content increase was clearly observed (*Figure 2*a). *Figure 2*b showed that the volumetric heat capacity of both materials varied in the same range. The range variation of w has a negligible impact on the thermal diffusivity of both

materials. The results obtained in the 1st and 2nd series are in agreement with literature. They therefore validated the experimental procedure used in this study.

3.3. Mineralogy and particle size effect on thermal properties (3rd series)

The mineralogy of the sample has an effect on its thermal conductivity (Ekwue et al. 2006, Zhang et al., 2017). For example, Brigaud and Vasseur (1989) denoted that the λ of quartz (λ_{quartz} = 7.7 $W.m^{-1}.K^{-1}$) is higher than that of illite (λ_{illite} = 1.85 $W.m^{-1}.K^{-1}$). As a consequence, the addition of sand to illitic material provided a higher λ for the S+I samples in comparison with the illitic samples (*Figure 2a*).

3.4. Coupled effect of water content and dry densities on thermal properties (4thseries)

The coupled effect of water content and dry density was studied by measuring the thermal parameters of samples compacted on several points of the compaction curves of five materials (illite (I), illite+sand (S+I), Plaisir loam (PL), sand+Jossigny loam (S+JL), sand+Xeuilley loam (S+XL)) of varying size distribution and mineralogy. Measurements of thermal parameters (λ, C and α) were carried out on samples prepared with the same compaction energy.

The results (*Figure 3*) showed that the thermal conductivity of each material increased on the dry side of the compaction curve until reaching a maximum near the Proctor optimum. On the dry side of the compaction curve, the dry density and the water content both increased, resulting in an increase of λ. In contrast, on the wet side of the compaction curve, the evolutions are different according to the sample mineralogy. For the silicious materials (S+I, PL, S+JL, S+XL), λ decreased, whereas for the silicate material (I), λ remained at its highest values. These evolutions are consistent with the physical properties of the studied samples. On the wet side of the compaction curve, the water content continues to increase, whereas the dry

density decreases. As the saturation rate remains approximately the same, the water molecules took the place of solid grains. As λ_{quartz} (7.7 $W.m^{-1}.K^{-1}$) is higher than λ_{water} (0.61 $W.m^{-1}.K^{-1}$) (Brigaud & Vasseur, 1989), the thermal conductivity of samples containing quartz decreased quite quickly, whereas the thermal conductivity of samples containing silicates (λ_{illite} =1.9 $W.m^{-1}.K^{-1}$) remained at an approximately constant value.

The volumetric heat capacity of soils increased on the dry side of the compaction curve until reaching a maximum near the Proctor optimum. Then, the values remained constant or decreased slightly. The variation range of the volumetric heat capacity was identical for the five materials studied.

The thermal diffusivity followed the same variation as the thermal conductivity in accordance with its definition ($D=\lambda/C$). Consequently, the thermal diffusivities of sand-loam mixtures (S+JL and S+XL) were three times higher than that of the illitic soil.

3.5. Combined effect of water content, dry density and temperature variations on thermal properties (5th series)

According to the potential use of compacted soils near a heat source or heat sink (energy storage, buried cables, or waste storage), the effect of temperature on the thermal properties was studied within a maximum temperature range of 1 to 70°C. Samples were prepared at various w and ρ_d under the same compaction energy (standard Proctor). Three materials were investigated: the illitic material (I, *Figure 4*), the sand-illitic soil mixture (S+I, *Figure 5*) and the Plaisir loam (PL, *Figure 7* and *Figure 8*). Thermal diffusivity measurements for the I samples were quite scattered due to their very low values compared with the measurement range (*Table 4)*. In the studied temperature range, the main evolutions obtained in the previous part were observed for each material:

- thermal parameters reached their maximum values near the Proctor optimum;
- thermal parameters increased on the dry side of the compaction curve;

- thermal parameters remained at their maximal values on the wet side of the compaction curve for illitic samples; and
- thermal parameters decreased on the wet side of the compaction curve for the S+I and PL samples.

Following this general trend, variations were noticed according to the sample temperature. An extensive experimental study was carried out on the illitic material, which was expected to be the material most sensitive to temperature variation. The uncertainty of this method (10%) is presented with a double arrow for one point of each series (*Figure 4*a, b and c). The variation of λ in the temperature range of 1 to 40°C was within this uncertainty interval, but for 70°C results have clearly shown an increase of λ with increasing temperature. Measurements performed on S+I and PL over a maximal temperature range of 1–50°C confirmed this trend.

The increase of thermal conductivity linked to the sample temperature was more important on the dry side than on the wet side of the compaction curve. This phenomenon is in addition to the increase of λ linked to the dilatation of the components (water and minerals) with increasing temperature.

In a saturated soil, the heat flux moves through solids and liquids by diffusion. Convection movements may aid the transfer, but the liquid convection may be limited, especially in low permeability materials. In an unsaturated soil, at low saturation rates, as is the case on the dry side of the compaction curve, the material contains solids, water and air. The thermal conductivity of air is very low unless it contains water vapour. The water vapour moves through the pores, increasing the thermal conductivity of the material. At higher temperatures, the air is able to reach higher moisture contents, which increases its participation in thermal conduction.

The impact of temperature variations on the volumetric heat capacity was not as clear as that on λ, especially for the I and S+I samples. *Figure 4*b and 5b do not show a clear trend for the

evolution of this parameter. The impact of temperature variations seemed to be below the measurement sensitivity. For PL samples, C measurements at 50°C were higher than values at 20°C in the case of L1 samples (*Figure 8*). The thermal diffusivity increased with increasing temperature in accordance with the λ evolution (*Figure 4*c and 5c).

3.6. Cyclic temperature variation effect on thermal properties (6th series)

Several samples of Plaisir loam were submitted to cyclic variations of temperature. Different cycles of 20/50°C (*Table 6*) were applied to the samples that were hermetically closed to keep w constant. The measurements were performed at various steps of the temperature programmes, as defined in *Figure 6*.

The experimental results showed that heating the samples increased the thermal conductivity and the volumetric heat capacity. These results confirmed the trends obtained in the previous part.

The measurements after 60 cycles showed that the **thermal conductivity** λ_{PL} at 20°C after the thermal cycles (C3) was lower than λ_{PL} at 50°C (C2). Nevertheless, the value of λ_{PL} at 20°C measured after the cycles (C3) was slightly higher than λ_{PL} at 20°C measured at the beginning of the test (C1) (*Figure 7*). The thermal conductivity reflects the capacity of a material to conduct a heat flux, this difference can be due to a change in the soil structure after several cycles.

Measurements of the **volumetric heat capacity** at 20°C (C3) remained very close to those obtained in test (C1) (*Figure 8*). The volumetric heat capacity reflects the ability of a material to store energy, it may be considered as the sum of the participation of soil different component. The ratio between solid, liquid and air did not vary in the sample and the volumetric heat capacity remained unchanged.

4. Conclusions

The effects of dry density, water content, mineralogy, size distribution and temperature on the thermal conductivity, volumetric heat capacity and thermal diffusivity of five materials were studied in the laboratory. In accordance with previous studies, the thermal parameters of the studied materials increased with increasing dry density and water content. The samples with wider granularity had a higher density and better solid contacts that improved their thermal conductivity. The effect of water content on thermal conductivity was clearly observed in loose materials, whereas in denser materials, the effect was negligible. The thermal conductivity of materials increased with increasing quartz percentage and the spread of the granulometric curve, whereas the volumetric heat capacity of materials seemed less sensitive to variations in the mineralogy and particle size. In the compacted soils, the thermal conductivity, the volumetric heat capacity and the diffusivity increased on the dry side of the compaction curve until reaching a maximum near the Proctor optimum.

The effect of temperature variation on the thermal properties was studied within a maximum temperature range of 1 to 70°C. The thermal conductivity and thermal diffusivity increased significantly on the dry side of the compaction curve and at high temperatures (illitic soil at 70°C), while the effect of temperature on the specific heat capacity was not significant. The increase in thermal conductivity induced by temperature variation was more important on the dry side than on the wet side of the compaction curve due to the water vapour movement. Heating the samples increased the thermal properties, but this modification is partially reversible after several cycles for thermal conductivity and totally reversible for volumetric heat capacity.

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400 *Table 1. Mineralogical composition of the raw materials*

Material	Ref.	Quartz	calcium carbonate	Feldspar	clay minerals	Others
Illitic soil	I	Traces	12% Calcite	Traces	77% Illite 10% Kaolinite	
Plaisir Loam	PL	81%	5% Calcite 7% Dolomite	3%	5%	
Jossigny Loam	JL	98%	Traces	1%	1%	
Xeuilley Loam	XL	83%	2%	3%	11%	1% Goethite
Hostun Sand	S	97.4%	Traces			2.6%

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404 *Table 2. The characteristics of the studied materials*

Properties	Illitic soil I	Plaisir loam PL	Jossigny loam JL Fleureau & Inderto (1993)	Xeuilley loam XL Blanck et al. (2011)
Grain size distribution				
Passer - by 80 μm	100	41	80	95
Passer - by 2 μm	85	20	28	25
Atterberg limits				
Plastic limit (%)	34	20.6	16 - 19	28
Liquid limit (%)	65	27.3	37	37
Plasticity index	31	6.7	18 - 21	9
Specific surface				
MBV(g/100g)	5.41	1.85	-	3.1
Carbonate content				
$CaCO_3$	-	0.8	-	1.3
Proctor compaction				
w_{OPN} (%)	31.3	16	15.5	18.5
γ_{dmax}/γ_w	1.43	1.81	1.75	1.71
γ_{max}/γ_w	1.88	2.10	2.02	2.03
Soil Class				
GTR Classification	A3	A1	A2	A2
USCS Classification	MH	CL	CL	ML

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412 *Table 3. Composition and parameters of the standard Proctor curve for the mixtures*

Mixture	Composition	w_{OPN} (%)	ρ_{dmax} (Mg/m^3)	ρ_{hOPN} (Mg/m^3)
S+I	50% Hostun sand and 50% Illitic soil	18.6	1.71	2.03
S+JL	50% Hostun sand and 50% Jossigny Loam	13.6	1.89	2.15
S+XL	50% Hostun sand and 50% Xeuilley Loam	13.7	1.88	2.14

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418 *Table 4. Performed tests as a function of material type*

Series	Variables	Materials				
		I	S+I	PL	S+JL	S+XL
1	γ	+	+			
2	w	+	+			
3	mineralogy and particle size	+	+	+		
4	w and γ	+	+	+	+	+
5	w and γ and T	+	+	+		
6	w and γ and T (cycle)			+		

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421 *Table 5. Range and precision of sensors SH-1 and TR-1*

Sensor	Propriety	Measure range	Precision
TR-1	Thermal conductivity ($W.m^{-1}.K^{-1}$)	0.1 - 0.2 0.2 - 4	± 0.02 ± 10 %
SH-1	Thermal conductivity ($W.m^{-1}.K^{-1}$)	0.02 - 0.2 0.2 - 2	± 0.01 ± 10 %
SH-1	Thermal diffusivity (mm^2/s)	0.1 - 1	± 10 %
SH-1	Volumetric heat capacity ($MJ.m^{-3}K^{-1}$)	0.5 - 4	± 10 %

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428 *Table 4. Temperature programme applied on PL (6th series)*

Program	Stage 1		Stage 2		NB cycle
	T°C	Time	T°C	Time	
P1	20	9h	50	9h	60
P2	20	2h	50	4h	60
P3	20	9h	50	9h	4

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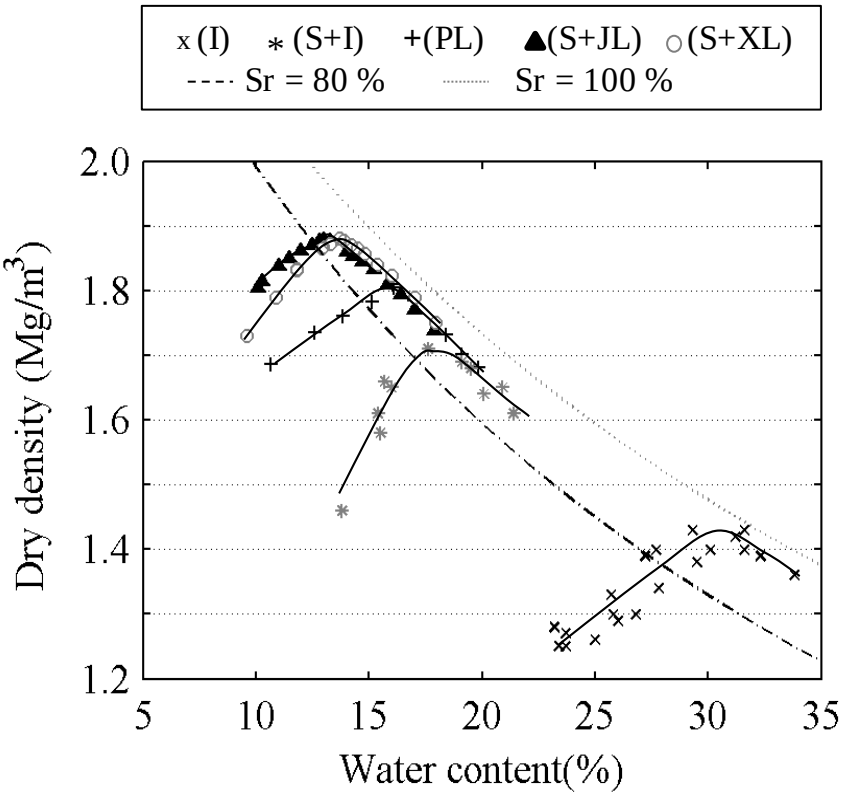

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435 *Figure 1. Compaction curves of the studied materials.*

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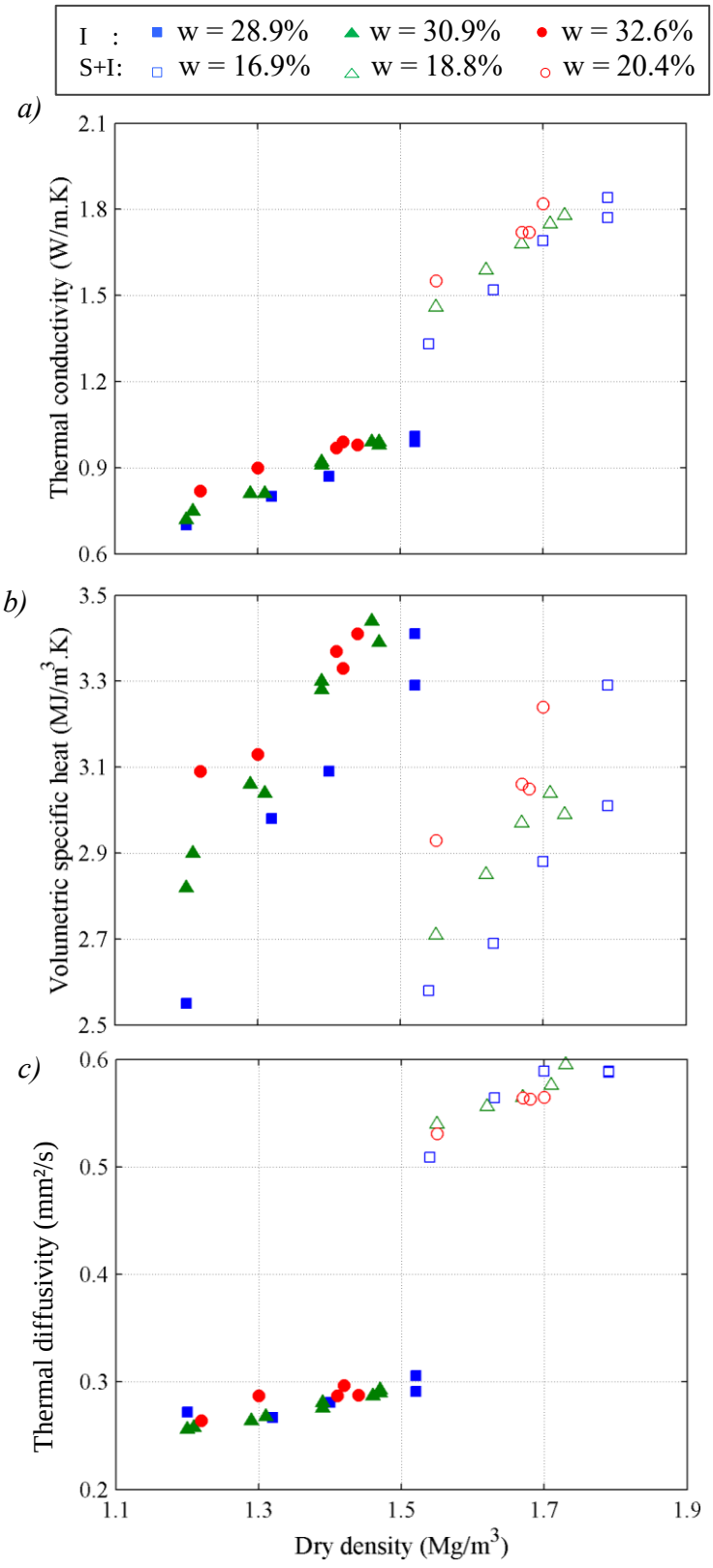
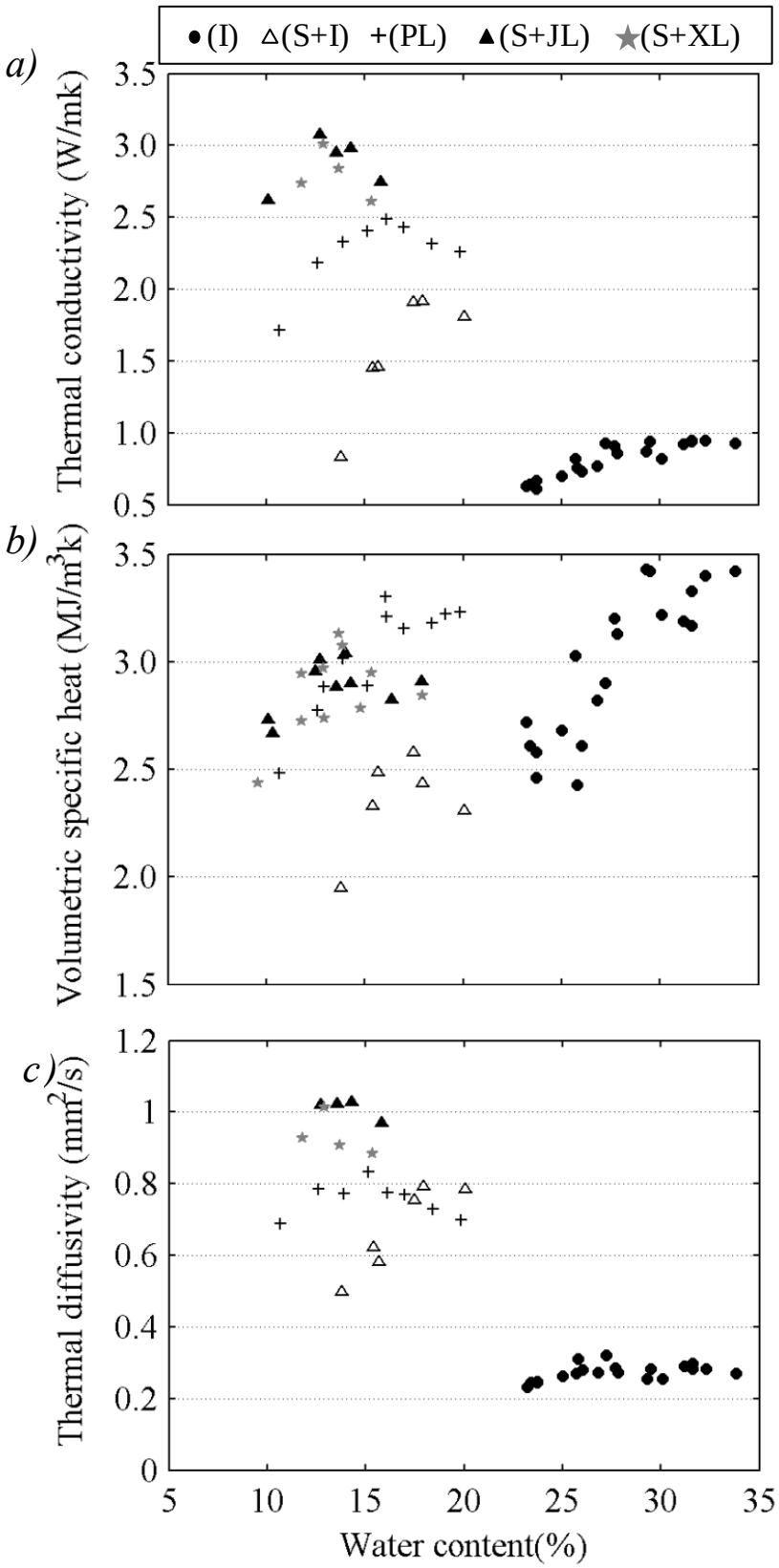


Figure 2. Evolution of the (a) Thermal conductivity, (b) Volumetric heat capacity and (c) Thermal diffusivity as a function of dry density at different water contents for the illitic material (I) and the sand-illitic material mixture (S+I) (1st and 2nd series).



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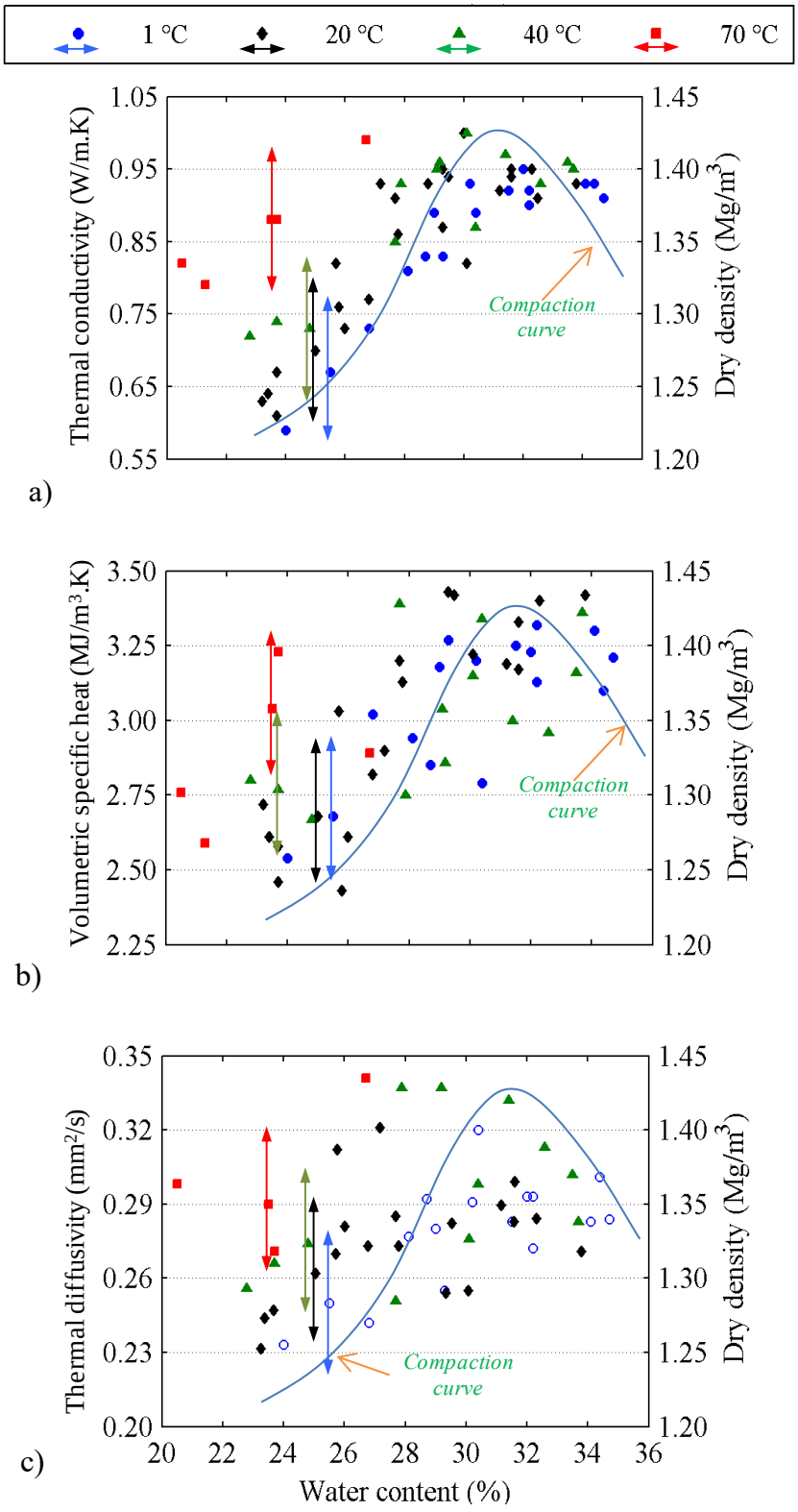
445 *Figure 3. (a) Thermal conductivity, (b) Volumetric heat capacity and (c) thermal diffusivity as*

446 *a function of water content and dry density of materials (4th series).*



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449 *Figure 4. Evolution of the thermal properties of the illitic soil (I) according to the*

450 *temperature and uncertainty (double arrow) : (a) Thermal conductivity, (b) Volumetric heat*

451 *capacity and (c) Thermal diffusivity (5th series).*

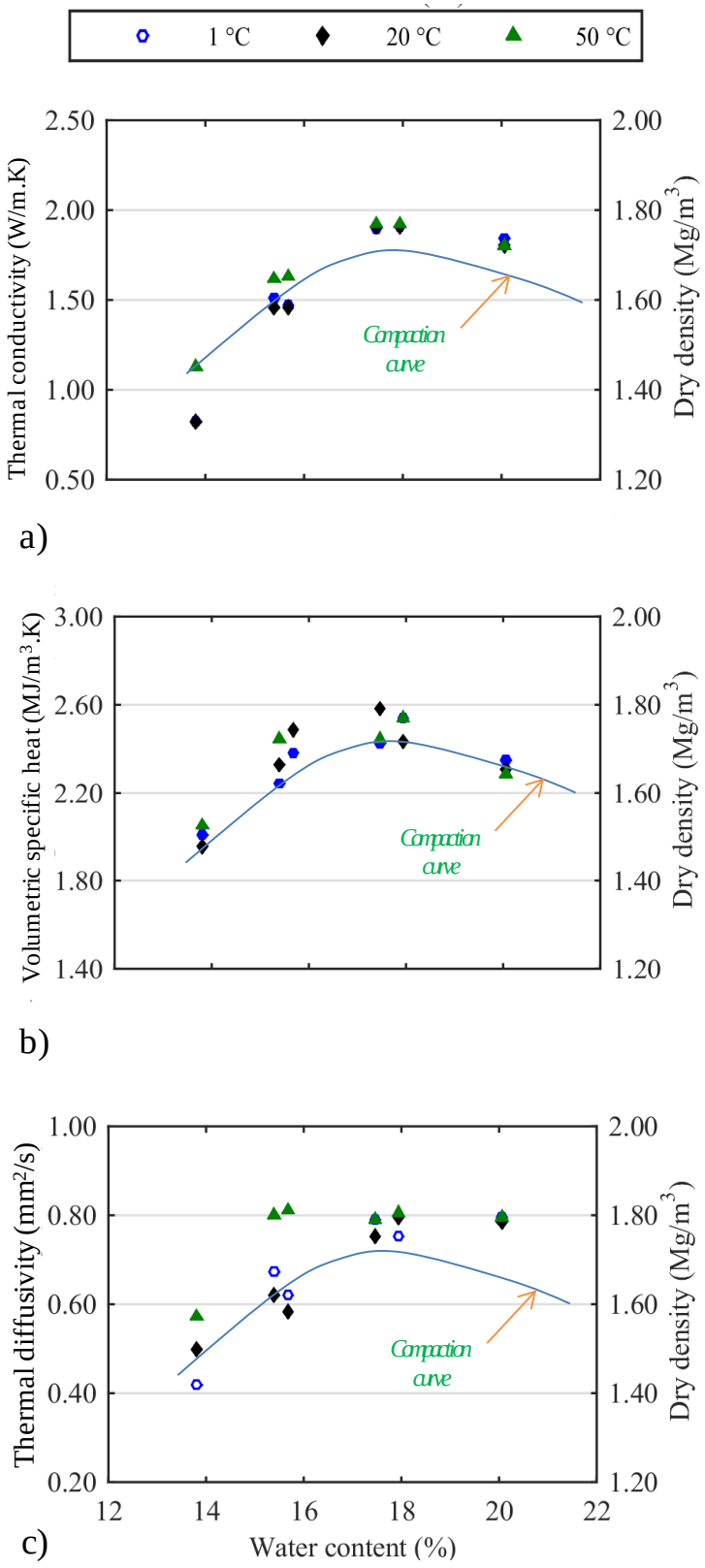


Figure 5. Evolution of the thermal properties of the sand-illitic soil mixture (S+I) according to the temperature: (a) Thermal conductivity, (b) Volumetric heat capacity and (c) Thermal diffusivity (5^{th} series).

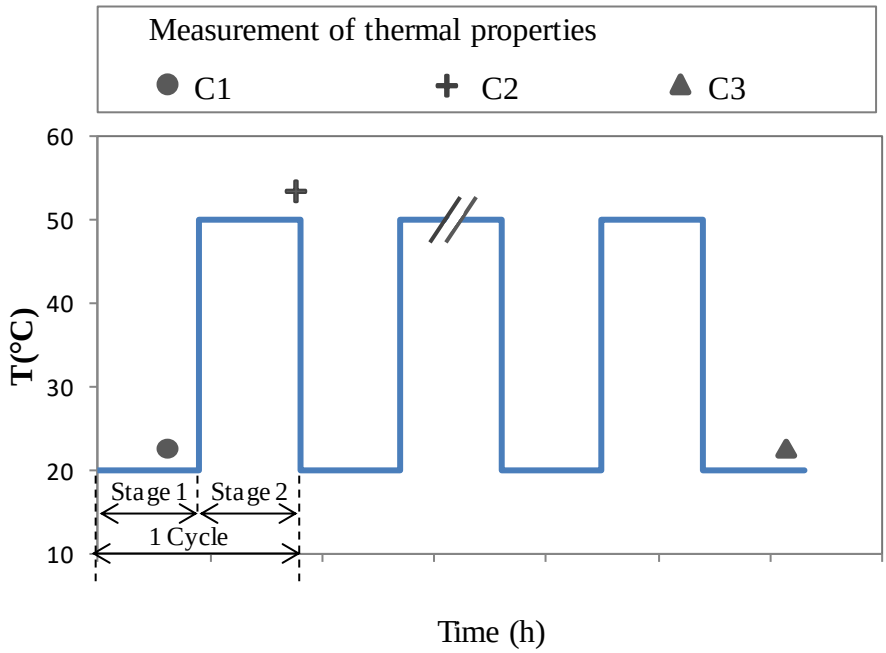
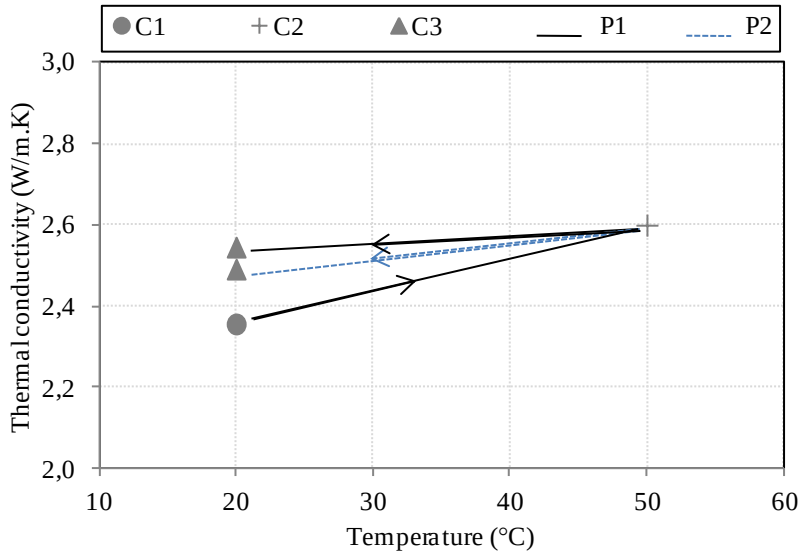


Figure 6. The chronology of measurements as a function of cyclic temperature variation applied to the PL samples (6^{th} series).



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463 *Figure 7. Warming effect on thermal conductivity of PL (P1, P2, 6th series).*

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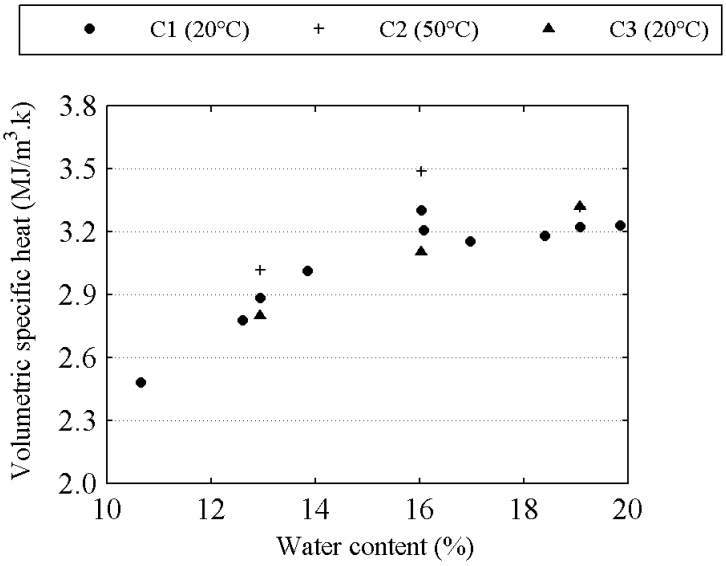

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467 *Figure 8. Warming effect on volumetric heat capacity of PL (P3, 6th series).*