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Thermal properties of a tropical unsaturated soil

Thaise da Silva Oliveira Morais[1,*], *Cristina de Hollanda Cavalcanti* Tsuha[1], and *Orencio Monje* Vilar[1]

[1]University of São Paulo at São Carlos, Departament of Geotechnical Engineering, Av. Trabalhador Sancarlense, 400, São Carlos, SP, 13566-590, Brazil.

Abstract. Ground thermal properties, especially the thermal conductivity, are of paramount importance for the design of ground source heat pump systems (GSHP), used for space heating and cooling. However, very little information, if any, are available from the thermal characteristics of tropical unsaturated soils related to the GSHP application. To evaluate the thermal behaviour of a typical Brazilian tropical unsaturated soil, an extensive experimental investigation was conducted at the test site of the University of Sao Paulo at São Carlos (EESC/USP) comprising a detailed soil characterization; field monitoring of the seasonal groundwater table variation; soil and ambient temperatures, and matric suction of the top soil. This paper describes the investigation program and compares the thermal soil properties as measured in laboratory and field thermal response tests. The results were variable depending on the testing techniques; however, all results showed that the soil thermal conductivity is strongly influenced by the degree of saturation of the soil.

1 Introduction

Soil is a porous three-phase medium (solid grains, water and gases) capable of storing and allowing process for the transfer of water, solutes, gases and heat. Currently, demands related to geotechnical and geo-environmental problems such as remediation of contaminated areas, disposal of radioactive waste, design of buried cable lines and, more recently, the use of shallow geothermal energy, have highlighted the soil as a multiphase natural material where heat exchange mechanisms occur.

The transfer of thermal energy (termed heat) in the soil due to a temperature gradient occurs until the thermal equilibrium is reached (temperatures become equal) [1, 2]. According [3], the soil´s capacity to store and transfer heat is a function of its thermal properties and the climatic conditions at the site.

Due to its composition, the heat transfer in the soil is complex and involves conduction mechanisms (through grains, liquids and gases), convection (through diffusion and absorption process of the present fluids, liquid and vapour) and radiation. In addition, it is also possible to consider processes of vaporization, condensation (during the water phase change), ion exchange, freezing and thawing [4 – 6]. In soils, the conduction heat transfer is the dominant process, followed by convection [3, 7]. Convection, can take place by liquid diffusion, for the case of saturated soils and also by vapor diffusion in unsaturated soils. Radiation, on the other hand, does not considerably influence heat transfer in soils, being neglected for thermal exchange in depth, but it must be considered in analysis of thermal exchange between environment and the ground surface zone [2 – 6].

It is fundamental to know the soil thermal properties to understand and estimate the propagation and storage of heat in the ground. To characterize the soil of a given area as a source and/or reservoir of thermal energy, it is necessary to consider its thermal inertia properties, which are determinant to the process of thermal exchanger and directly influence their thermal behaviour [3, 8]. Rees et al. (2000) [6], Farouki (1981) [7] and CFMS & Syntec (2017) [9], highlight that these thermal properties varies according to the properties and proportions of the soil phases (solid fraction: mineral and organic, water and air).

During the last six years, a comprehensive investigation has been carried out to determine the thermal properties of the unsaturated soil at the test site of the University of Sao Paulo at São Carlos, Brazil [10 – 14]. The current paper presents the results of soil thermal properties, considering local field condition, obtained from field and laboratory thermal tests.

2 Soil Thermal Properties

2.1 Thermal Conductivity (λ)

The thermal conductivity is an intrinsic property of the material in a steady state of heat conduction and, for soils, can be simply defined as its heat conduction capacity. The soil thermal conductivity (λ) is defined by Eq. (1), which express the capacity to conduct heat per

* Corresponding author: tsomorais@sc.usp.br

unit cross-sectional area of the soil due to the imposition of a temperature gradient in the same direction of the heat flow.

$$\lambda = \frac{q}{A(\nabla T/l)} \quad (1)$$

Where q is the heat flow (W), A is the cross sectional area to heat flow (m²), ∇T is the temperature gradient (K) and, l is the distance travelled by the heat flow (m).

The conduction heat transfer in the soil occurs first in the solid phase and is limited by the contacts between particles, seconded by conduction transfer in the phases that fill the soil pores, which can represent an important contribution in the global thermal conductivity of the soil [2]. Oh (2014) [15] comments that the global soil thermal conductivity is not a single value parameter, but it depends on the conductivity of each phase that constitutes the soil and physical factors as water content, porosity, density, mineralogical and chemical properties [4, 7, 6, 15]. Additionally, CFMS & Syntec (2017) [9] emphasize that these factors do not act in a linear way on the global soil thermal conductive, and as a result, a soil will be more conductive if presents: low porosity, considerable quartz content, and moisture condition close to saturation.

Di Sipio and Bertermann (2018) [16], considering all the soil constituents phases, states that the range of thermal conductivity values can be summarized as follows: $\lambda_{air} < \lambda_{dry\text{-}soil} < \lambda_{water} < \lambda_{saturated\text{-}soil} < \lambda_{mineral}$, where: λ_{air} = 0.026 $Wm^{-1}K^{-1}$, λ_{water} = 0.56 $Wm^{-1}K^{-1}$ and $\lambda_{mineral}$ = 3.0 $Wm^{-1}K^{-1}$.]Thus, the mineral portion responds for most of the thermal conductivity, confirming the predominance of heat flow through soil solid phase [16, 17]. However, as the thermal conductivity of air is less than that of water, dry soils tend to present lower thermal conductivities than saturated soils. Di Sipio and Bertermann (2018) [16] still mentioned that for the same saturation condition, granular soils will tend to present better thermal response than fine-grained or cohesive soils, due to quartz content. Typical thermal conductivities values of some soils and rocks are presented in Table 1.

Table 1. Thermal properties of some soils and rocks, according Lhedup et al. (2014) and Barry-Macaulay et al. (2013) [18, 19].

Material	λ ($Wm^{-1}K^{-1}$)	C_v ($kJm^{-3}K^{-1}$)
Gravel	2.00 – 3.30	2200 – 2700
Sand	1.50 – 2.50	2500 – 3000
Silt	1.40 – 2.00	2500 – 3100
Clay stone	2.60 – 3.10	2340 – 2350
Sandstone	3.10 – 4.30	2190 – 2200
Saturated Sandstone	2.46 – 2.84	-
Dry Sandstone	1.04 – 1.67	-
Saturated Siltstone	1.73 – 2.47	-
Dry Siltstone	0.72 – 1.54	-
Saturated Basalt	1.08 – 1.57	-
Dry Basalt	0.56 – 1.05	-

2.2 Heat Capacity

The increase of temperature in a soil is dependent on how much heat is transferred (λ) and the thermal capacity of each soil phase (mineral solids, water and air) [3]. Therefore, it is possible to define the soil heat capacity (C) as the amount of heat required to change the temperature of the soil by a certain amount (unit in J/K or J/°C).

Taking the soil phases expressed throughout each volumetric fraction, the soil specific volumetric heat capacity (C_v) can be defined as the amount of thermal energy that 1 m³ of soil stores before its temperature rises by 1 K or 1 °C (with unit in J/m³K or J/m³°C). C_v can be derived from the specific gravimetric heat capacity (c_g) and the soil density (ρ), representing the weighted average of soil phases [4]. Therefore, in a multicomponent system as the soil, the heat capacity (c_g, C_v and C) can be estimated, from the Eqs. 2 to 4 [3, 4, 6].

$$c_g = c_{gs} f_{gs} + c_{gw} f_{gw} + c_{ga} f_{ga} \quad (2)$$

$$C_v = c_{gs} \rho_s f_{vs} + c_{gw} \rho_w f_{vw} + c_{ga} \rho_a f_{va} \quad (3)$$

$$C = x_s c_{gs} \rho_s + x_w c_{gw} \rho_w + x_a c_{ga} \rho_a \quad (4)$$

Where:
c_{gs}, c_{gw} e c_{ga} – especific gravimetric heat capacities of the solid, water and air soil portions (J/kg K or J/kg °C);
f_{gs}, f_{gw} e f_{ga} – solid, water and air soil portions in terms of mass (kg/kg);
ρ_s, ρ_w, ρ_a – bulk densities of solids, water and air (kg/m³);
f_{vs}, f_{vw} e f_{va} – solid, water and air soil portions in terms of volume (m³/m³);
x_s, x_w e x_a – volumes of solids, water and air of soil (m³).

The last terms in equations 2 to 4 are generally not considered due to the low contribution of the air phase [3]. Thus, Brandl (2006) [4] presents Eq. 5 for the calculation of the specific volumetric heat capacity of the soil.

$$C_v = \rho_d \times \left(c_{gs} + c_{gw} \frac{w}{100} \right) \quad (5)$$

Where, c_{gs}, c_{gw} are especific gravimetric heat capacities of the minerals of the soil and water (J/kg K or J/kg °C) ; w is gravimetric water content of the soil and ρ_d the dry density. For c_{gw}, Brandl (2006) [4] suggested adopting 4,186 J/kg K and, for c_{gs} suggest a value of 1,000 J/kg K for most minerals present in the soil. However, Rees et al. (2000) [6] suggest a value of 2,010 J/kg K for c_{gs} of a quartz sand.

2.3 Thermal Diffusivity (α)

Thermal diffusivity (α) is the property that indicates how quickly heat diffuses through a material. In other words, α is the property that relates the material's ability to conduct thermal energy in relation to its thermal energy storage capacity, (unit in m² / s).

According to Brandl (2006) [4], α quantifies the depth and speed of penetration of a temperature wave in the ground and, according to Holman (1993) [20], the higher α, the faster the heat will be diffused through the material. Mathematically, α is the ratio between λ and C_v, representing the measure of the thermal inertia of the soil, as shown in Eq. 6.

$$\alpha = \frac{\lambda}{\rho \times c_g} = \frac{\lambda}{C_v} \tag{6}$$

Therefore, equation 6 shows that α is the relationship between the soil's ability to transmit thermal energy versus its ability to store thermal energy. Thus, from this equation, a high value of α can be the result of either a high λ or even a low C_v, or the combination of both conditions.

2.4 Soil Thermal Properties for Design of GSHP Systems

GSHP systems is a technology used for space heating and cooling based on the premise that the temperature of the subsoil is constant along depth and then, the ground can be used as heat exchanger, due to the stability of the average temperature along the year, and greater thermal capacity compared to the air [8, 21]. The thermal stability of the ground allows the seasonal operation of GSHP systems which, depending on the building's thermal demand, can extract heat from the ground during winter and injected into the ground during summer. The ground thermal stability and properties allow that the GSHP systems could be significantly more efficient than the traditional conditioning systems [4].

The ground thermal conductivity is one of the most important design parameters. According to Farouki (1981) [7], the ground thermal conductivity is the parameter that governs the steady state in the heat transfer while thermal diffusivity is applied to cases of transient heat transfer. Both of these ground thermal parameters are input data for analytical and numerical models used in the design and performance analysis of GSHP systems.

According to [7, 18], the ground thermal properties can be estimated from: literature data, empirical or semi-empirical formulations, and experimentally via laboratory or field tests. However, the results obtained by formulations and laboratory tests may not accurately represent the real thermal properties of the soil mass along the length of the ground heat exchanger (closed loop system), as well as the stress state, anisotropy, soil structure, the presence of a groundwater flow and other aspects. Nevertheless, despite the limitations, laboratory thermal tests represent an efficient technique for the determination of ground thermal properties, as it is fast to perform and offers immediate results.

3 Unsaturated Tropical Ground Studied

Brazil is a country of continental dimensions, with predominance of tropical and subtropical climates, and high temperatures in its five regions. An important area of this country is covered by unsaturated soils that in many instances are of lateritic nature. Laterization processes causes silica and bases removal and the migration of fines forming a porous soil composed by the more resistant minerals, such as quartz. The fine fraction is composed by iron and aluminium oxides, and kaolinite as the predominant clay mineral

3.1 Test Site

In the current paper, the tropical unsaturated soil investigated is located at the Foundation Test Site of the University of São Paulo at São Carlos city, São Paulo state, in the southeast region of Brazil. The climate is classified as high-altitude tropical, with dry winters (May to August) and rainy summers (September to April), with the average annual temperature varying from 12 to 28°C.

The unsaturated tropical soil at this site is composed of two different layers: (1) a superficial colluvial clayey sand (cenozoic sediment, originated from Bauru and Botucatu sandstone and from magmatic rocks of Serra Geral Formation), lateritic, porous and of collapsible nature, with a thickness of approximately 7 m; (2) a residual soil of sandstone of clayey sand from Bauru Group (Itaqueri Formation). Between these two soil layers there is a pebbles deposit (stone line), composed of quartz and limonite, which separates the upper cenozoic sediment and oldest residual soil layer [22 – 24]. The groundwater table (gwt) at the test site varies seasonally from around 9 to 12 m below the ground surface, according to the monitoring results presented by [13, 14], obtained from 2014 to 2018. During this period, the deeper levels of the groundwater table were generally observed between April and July.

Machado (1998) [24] presented a geotechnical characterization of the soil at the test site, obtained by laboratory tests performed on undisturbed soil samples (between 1 m and 9 m depth). Fig. 1 summarizes part of these results, combined with the results of soil chemical characterization, and ground temperature (from Piezocone Resistivity tests, RCPTu).

Machado and Vilar (2002) [23] mentioned that the ground at this test site is composed of mainly quartz and oxides. The chemical results from X-ray fluorescence spectrometer, showed in Fig. 1 [13, 14], combined with the results from X-ray diffractometer [13], confirm the soil composition mentioned by [23]. In quantitative terms, at least 60% of the soil is composed of quartz and 30% of oxides (Al_2O_3 and Fe_2O_3), increasing the proportion of quartz with depth.

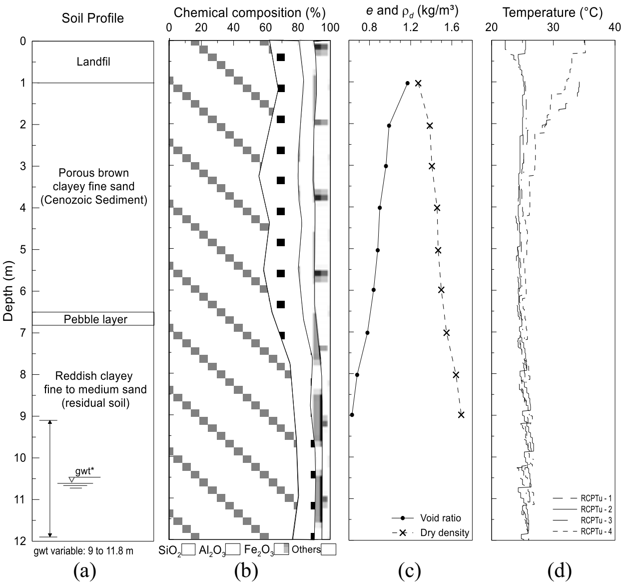

Fig. 1. Soil characteristics at test site: a) soil profile and seasonal variation of the groundwater table (gwt) [13, 14], b) soil chemical composition [13, 14], c) void ratio (e) and dry unit mass (ρ_d) [24] and d) in situ temperature from RCPTu tests [25].

To characterize the unsaturated soil of the studied case, soil-water retention curves (SWRC) obtained by [24] for the soil at 2, 5 and 8 m depth in the test site, are presented in Fig. 2. The SWRCs show a very low air entry value (nearly to zero).

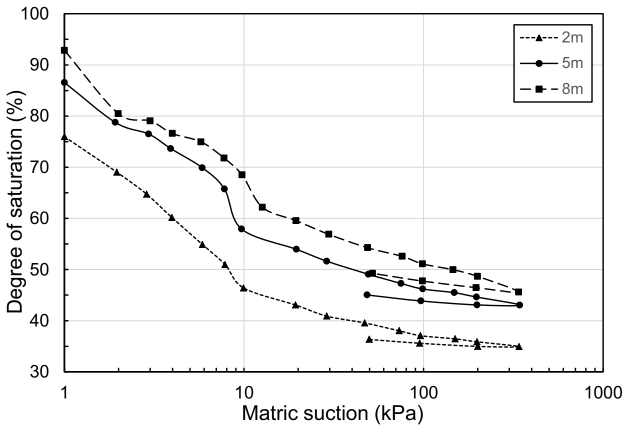

Fig. 2. Soil-water retention curves of some soil layers at the EESC/USP test site [24].

4 Ground Monitoring and Thermal Tests

The soil profile was investigated up to 12 m depth. For a better interpretation of the results of ground thermal conductivity values, obtained from laboratory and field tests, an extensive field monitoring program was implemented to verify the influence of the seasonal variation of the unsaturated soil condition on the results.

4.1 Monitoring of unsaturated ground conditions

Considering that the ground thermal properties can be influenced by the local climatic characteristics and consequent variation of soil saturation condition, a continuous field monitoring was carried out by [13, 14], during the period from 2014 to 2018.

The field monitoring included measurements of groundwater table fluctuation, ambient and ground temperature, precipitation, gravimetric water content along the depth at different periods of the year, and matric suction of the top soil by tensiometers. More details of the field monitoring are provided by Morais (2019) [13] and Morais et al. (2020) [14].

4.2 Field thermal response tests

The field thermal conductivity was determined by thermal response tests (TRT) performed on an energy pile with 12 m length, 250 mm diameter and with a single high-density polyethylene (HDPE) U-loop installed along pile length. The energy pile was constructed in 2014 at the test site, and the details of the pile construction, the TRTs tests, and the TRT equipment constructed for this study are described by [14].

Seven TRT tests were carried out on the energy pile during the period from 2015 to 2018 to investigate the effect of the seasonal variation of soil saturation on the thermal conductivity of the soil along the pile shaft. To measure the thermal response of the soil around the pile during the tests, two boreholes (BH1 and BH 2) were constructed for the installation of PT 100 thermo resistors in the soil at three depths: 3.5, 7.5 and 11.5 m.

The main result of a TRT test is the thermal resistance of the pile or the borehole heat exchanger (R_b) and the effective thermal conductivity (λ_{eff}) of the soil along the heat exchanger, which represents the average soil thermal conductivity of the different soil layers along the length of the vertical heat exchanger (borehole or pile).

The TRT involves applying a constant heat power to the ground by a forced flow of a heat exchanger fluid inside ground heat exchange tubes (HDPE) installed in a borehole or pile. During the test, the fluid flow rate and the inlet and outlet fluid temperatures are continuously monitored. The minimum duration of the test depends on the soil properties and the characteristics of the vertical heat exchanger (diameter, length and filling material).

Results from TRT can be analysed by analytical or numerical methods, with the analytical Kelvin's linear heat source theory, or infinite line source model (ILS). ILS is the most widespread and used method, due to its simplicity and speed of analysis. It considers that the transfer of thermal energy in the test occurs from the fluid to the ground, taking into account the thermal resistance of the heat exchanger. The method is considered to be valid only during the period of steady state heat transfer.

4.3 Laboratory thermal cell tests

The thermal cell is a stationary laboratory test, proposed by Clarke et al. (2008) [26], for the direct determination of the thermal conductivity of the soil. It is based on the measurement of the thermal power supplied to the soil sample and on the monitoring of the temperature throughout the sample. In the pioneering version of the test, the soil sample was positioned between two cylindrical plates, which had built-in electrical resistances that were controlled to maintain different temperatures in these plates.

Low (2016) [27] developed a simpler thermal cell (UoS thermal cell), with only an aluminum plate at the base and only one electrical resistance. At the top of the sample, an aluminum sheet is placed to prevent soil moisture loss for the environment.

The soil thermal conductivity obtained from the thermal cell test can be determined using the Fourier Law for the conduction of heat (Eq. 7). Once the thermal power supplied to the soil sample during the steady state is known [26, 27], it is possible to calculate the value of the thermal conductivity, λ.

$$\lambda = \frac{Q \times l}{A \times \Delta T} \quad (7)$$

Where, Q is the amount of heat passing through the soil sample, A is the soil sample cross-section, l is the distance between the temperature measurement points, and ΔT is the temperature difference.

For the present investigation, a thermal cell equipment was built to test soil samples of the test site. This thermal cell, based on the UoS thermal cell presented in Low (2016) [27], has a thicker wood base, that supports an aluminium base, an acrylic concentric tube, and a thermal insulation of glass wool. Fig. 3 presents the details of the thermal cell.

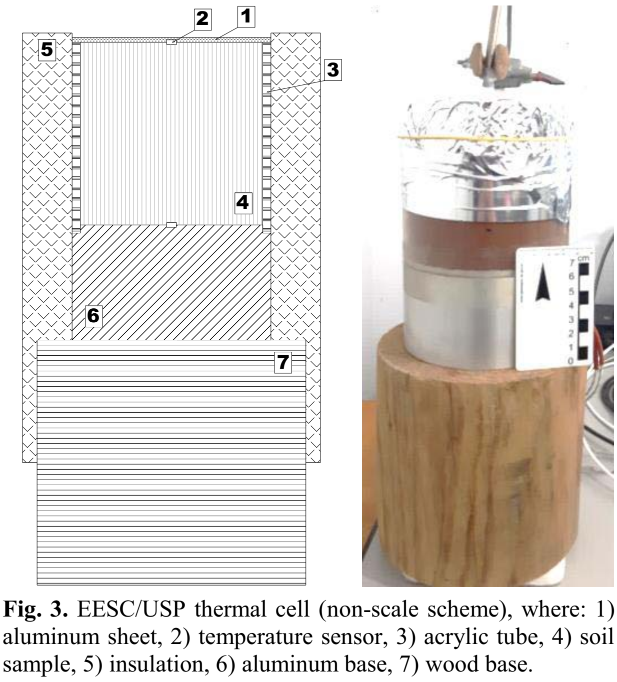

Fig. 3. EESC/USP thermal cell (non-scale scheme), where: 1) aluminum sheet, 2) temperature sensor, 3) acrylic tube, 4) soil sample, 5) insulation, 6) aluminum base, 7) wood base.

The aluminium base of the thermal cell has an electrical cartridge heater with 50 W of nominal power that allows to keep the base temperature constant during the test. It is activated by an automatic control via the data acquisition system connected to the temperature sensor at the base of specimen. The thermal cell was designed for tests on disturbed and undisturbed soil specimens (112 mm diameter and 111 mm height).

5 Results and Discussions

5.1 Field tests and monitoring

The seasonal thermal behaviour of the unsaturated tropical soil of the test site was investigated from 2014 to 2018. The environmental temperature results were obtained from the Brazilian National Institute of Meteorology (INMET).

During these years, the results of compensated average temperature, which is the daily average of three temperature measurements plus the maximum and minimum temperatures during the day, showed a variation from 16.5 to 25°C, between cold and hot seasons. However, the monitoring of soil temperature along the depth at test site showed that up to 3.5 m depth (unsaturated top soil) the ground temperature is strongly influenced by the environmental conditions. The influence of the air temperature decreases with the depth, and was not observed at the depths of 7.5 and 11.5 m. The average natural temperature of the unsaturated tropical soil studied is approximately 24°C, in agreement with the values cited in [4] for tropical regions.

Fig. 4 presents the results of the field monitoring during the year of 2016. This figure indicates a lower difference between the soil temperatures at 7.5m and 11.5 m depth (thermally stable depths). It is also possible to observe that the seasonal variation of soil temperatures along the depth is a result of the spread of heat wave in the soil due to the local climatic conditions.

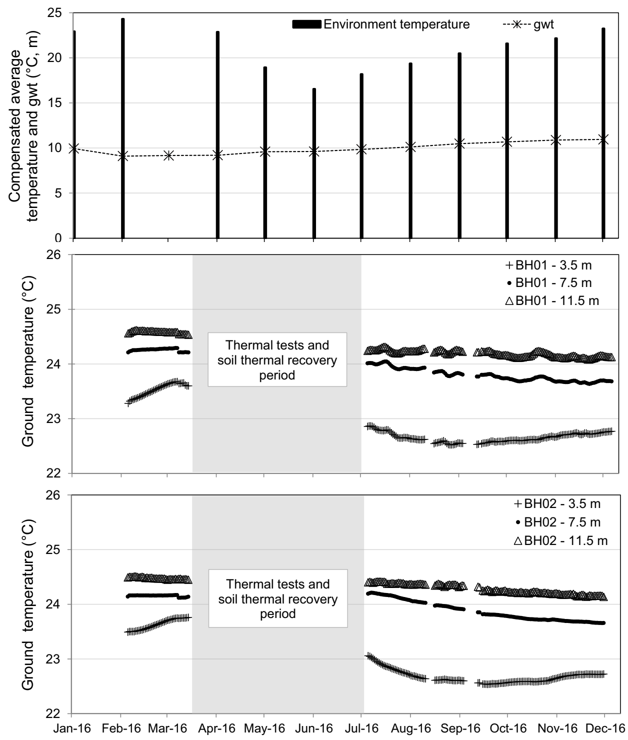

Fig. 4. Average results from: monthly ambient temperature in the city of São Carlos (from INMET), variation of the monthly depth of the groundwater table (gwt) and daily soil temperature along the unsaturated soil profile at EESC/USP test site, during 2016.

Fig. 4 also shows the average monthly depth of the groundwater table (gwt) at the test site during 2016 (averaging 10 m below ground surface, presenting a variation of +/- 1 m). The results of groundwater table variation during the monitored period from 2014 to 2018 shows a similar trend, with the average depth equal to 10.6 m, with a seasonal variation of +1.5 m and -1.2 m in relation to the average depth.

Fig. 5 presents the maximum and minimum values of the gravimetric water content (*w*) of the soil obtained from field monitoring [13, 14, 28]. This figure indicates that the seasonal variation of *w* decreases with soil depth, varying considerable between dry and rainy seasons. The smallest variation of *w* (between dry and wet seasons) was 20% at 8 m depth, reaching 36.9% at 1 m depth.

The variation of *w* represents the variation of the soil saturation degree (S_r), and explain the variation of the matric suction values found for the top soil layer at 1 m depth (from 14 to 70 kPa) [13, 14]. However, it is important to emphasize that the maximum and minimum values of gravimetric water content presented in Fig. 5 do not occur simultaneously, due to the seasonality of the rainfall and variation of the groundwater table position [14].

Fig. 5 also shows the results of C_v obtained from Eq. 5 and the limit values of *w* along the depth observed during field monitoring. This figure indicates that the values of C_v tend to increase with the soil depth, with a maximum seasonal variation of 15.8% at 1 m depth. The increase of C_v with depth is due to the increase of the dry unit mass (ρ_d, Fig. 1c) and of *w* with the soil depth. However, the minimum C_v values obtained (Fig. 5), correspond to the minimum *w* values, and are superior to 2000 kJm^{-3}K^{-1} (excluded the soil layer at 1 m depth).

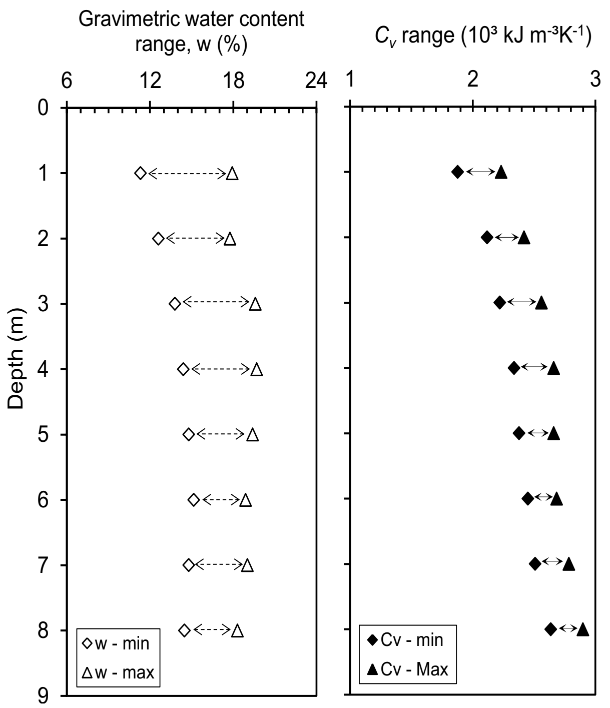

Fig. 5. *w* (%) and C_v (10^3 kJm^{-3}K^{-1}) values along the soil depth at the test site, obtained during the period from 2014 to 2018.

5.2 Field thermal response tests

The field investigation on the thermal conductivity of the unsaturated tropical soil at the test site was performed by Morais et al. (2020) [14]. These authors performed TRT test under different soil saturation conditions, and different groundwater table levels. They evaluated the effects of both parameters on the average value of λ_{eff} (effective thermal conductivity) of this tropical soil layer (0 m to 12 m depth).

The experimental investigation carried out by [14] indicated an average λ_{eff} of the soil profile equal to 2.94 Wm^{-1}°C^{-1}, with a coefficient of variation (CV) of approximately 12.9%. However, the authors identified a considerable difference in this average value between dry and rainy seasons, reaching approximately 32%, due to the combined effect of the variation of the groundwater table and of the saturation degree.

5.3 Laboratory thermal tests

Two thermal cell tests were performed to investigate the thermal conductivity of remoulded soil specimens, extracted from the test site at 2 m and 5 m depth. The specimens were molded taking into account the natural dry unit mass (ρ_d) of these soil layers, as well as the gravimetric water content (*w*) variation obtained from field monitoring (Fig. 5). The physical indices of the two specimens tested are presented in Tab. 2.

Table 2. Physical indices of the soil specimens.

Specimen	S_r (%)	*e*	γ_d (kN/m³)	γ (kN/m³)
2 m	44.79	1.00	13.52	15.76
5 m	40.13	0.89	14.32	16.21
	55.96	0.90	14.24	16.89

The soil specimens were prepared in the thermal cell by a process of static compaction in layers with previously known density (height and wet mass control). After that, the samples were submitted to thermal stabilization at an ambient temperature of 20°C, during a minimum period of 12 hours. After stabilization, the resistance was activated until reaching a temperature of 43°C at the base of the specimen, with a lower temperature limit being set for the automatic activation of cartridge heater. Fig. 6 presents the temperature results (ambient, base and top of the specimen) of two thermal cell tests performed.

The time to reach thermal stability (steady state) during the tests was approximately 5 hours (Fig. 6), being necessary about 15 hours for total thermal recovery.

The power supplied for the tests is different from the nominal power of cartridge heater, since the heater remains off and was automatically activated when the lower temperature limit at the base was reached. Therefore, the power supplied to the specimen during the heat injection phase of each test was obtained from the data acquisition system and a digital multimeter. The power that passes through the soil during the test was also reduced by 35%, as recommended by [27] for this type of test in soils.

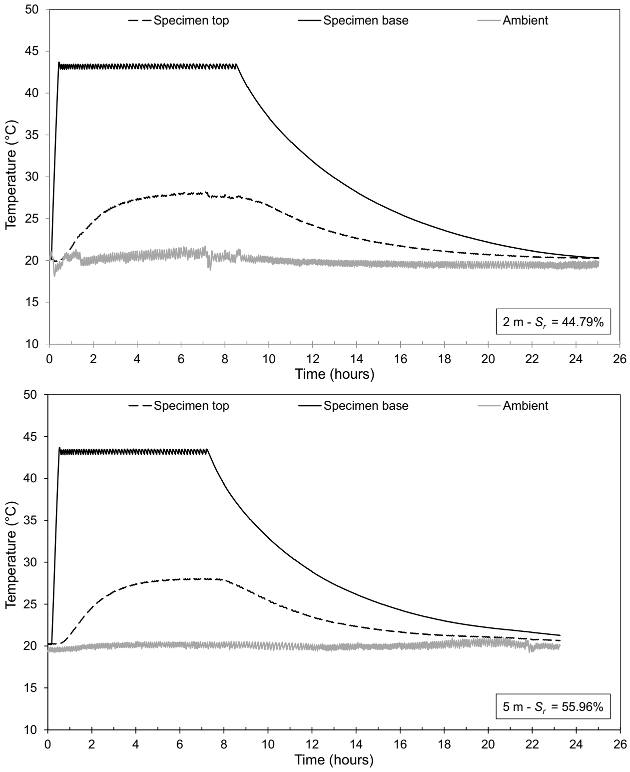

Fig. 6. Thermal cell results of the tests on unsaturated soil samples obtained at 2 m and 5 m depth (at the highest saturation condition tested).

Table 3 presents the results of soil thermal conductivity obtained by the thermal cell tests. The results shown in this table indicate that: (1) the thermal conductivity of the soil at 5 m depth is slightly higher compared to the soil at 2 m; (2) a higher value of λ was found for the soil at 5 m depth with higher saturation degree (as expected); (3) the soil thermal conductivity obtained from the TRT‘s are significantly higher compared to the results obtained by the thermal cell tests. This difference between laboratory and field results was also observed in previous studies [29].

Table 3. Thermal cell results.

Specimen	2 m	5 m	
S_r (%)	44.79	40.13	55.96
l (m)	0.111	0.111	0.111
A (m²)	0.010	0.010	0.010
T_{Base} (°C)	43.21	43.21	43.21
T_{Top} (°C)	27.97	26.64	27.94
Power (W)	1.83	1.96	2.07
λ ($Wm^{-1}°C^{-1}$)	**1.35**	**1.33**	**1.52**
C_v ($kJm^{-3}K^{-1}$)	**2335.5**	**2267.2**	**2584.3**
α (10^{-6} m^2s^{-1})	**0.58**	**0.59**	**0.59**
SiO_2 (%)	67.20	62.10	
Fe_2O_3 and AL_2O_3 (%)	23.90	28.51	
TiO_2 (%)	1.85	2.10	

6 Conclusions

The thermal properties of a Brazilian unsaturated tropical soil were investigated using field and laboratory tests, complemented by field monitoring. The results show that the degree of saturation influences the thermal conductivity and the thermal capacity of the soil. Therefore, in the current case studied of tropical unsaturated soil, the local climatic conditions causes a seasonal variation of the soil thermal properties along the year. In this study, the main conclusions are:

- The field monitoring results indicate that the temperature of the top soil zone up to 3.5 m is influenced by the ambient temperature. This influence decreases with depth, and at 7.5 m depth the temperature is practically constant throughout the year (~ 24°C).
- The effect of the degree of saturation on the soil thermal conductivity was verified using thermal cell tests. The increase of the saturation degree from ~40% to 56% caused an increase of 15.4% of the λ value for the soil extracted at 5 m depth.
- The results of soil thermal conductivity obtained from thermal cell tests were significantly lower than the average effective field thermal conductivity (λ_{eff}) obtained in [14] by TRT tests. The differences between laboratory and TRT test results can be related to large-scale in the field, quality of soil samples, field stresses, variation of moisture content, groundwater flow conditions, and other factors.

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