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Measurement of Thermal Conductivity of Unsaturated Tropical Soils by a Needle Probe Method

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Abstract. Geothermal energy piles (GEP) are a renewable energy technology that have been used as a cooling and heating source of building air-conditioning system. Brazil is currently the fifth largest buyer of air conditioner in the world, mainly due its tropical and subtropical climate, and the use GEP could be an interesting alternative to reduce the consumption of electrical energy for air-cooling systems. For an accurate design of energy foundations it is essential to estimate the ground thermal properties. However, the thermal properties of unsaturated tropical soils, that cover a significant part of the Brazilian territory, were not investigated before. These soils are products of weathering processes in tropical warm and humid climates, and generally present high contents of aluminum and iron oxides. To address that need, the current work was carried out to investigate the thermal properties of Brazilian unsaturated weathered soils of two different sites. For this study, thermal needle probe tests were performed on disturbed and undisturbed samples of tropical soils, and on silica sand under different moisture conditions for comparison. The results indicate that the particular mineralogical composition of the tropical soils investigated and the soil moisture content of sand have influence on soil thermal properties.

Keywords. Geothermal energy piles, soil thermal properties, unsaturated tropical residual soils, lateritic soils.

1. Introduction

The determination of soil thermal parameters is necessary for the analysis of engineering problems related to heat transfer mechanisms in the ground as thermal remediation of contaminated soils, disposal and storage of radioactive waste, insulation of electrical underground cables, freezing of soils to improve strength in construction and for stability and impermeability reasons [1, 2].

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Additionally, the soil thermal properties are also fundamental for the design of thermo-active structures used for the heat transfer between buildings and ground. Geothermal energy piles (GEP) are an example of thermo-active structure, used as heat exchangers for ground source heat pump systems (GSHP). The main advantage of GEP systems is that installation costs can be significantly reduced, as no additional excavation is required. For this reason, the use of GEP has been increased considerably after the 80's [3].

For the design of GEP systems it is necessary to estimate the soil thermal properties as thermal conductivity, thermal diffusivity and the natural temperature of the ground. The soil thermal conductivity is one the most important parameter in a GEP designing process, and can be obtained from laboratory or field tests [4 – 7]. Laboratory tests are an effective way to investigate the thermal properties of soils and rocks, allowing the analysis of the soil thermal properties under different conditions of saturation and density.

Brazil, due to its continental dimensions, possesses a very wide climatic diversification, with a predominance of wet equatorial, tropical and subtropical climates. According to government predictions [8], the demand for electrical power for air-conditioning systems (air cooling) in Brazil will have doubled by 2035. In this scenario, the use of GEP systems can be an interesting alternative to save electric energy consumption [9, 10]. Therefore, the determination of the thermal properties of typical Brazilian soils is essential for the future use of GEP systems in this country.

Unsaturated tropical soils cover a significant part of the Brazilian territory, and the thermal properties of these soils were not investigated before. In this context, the current work aims to investigate the thermal properties of Brazilian unsaturated lateritic and saprolitic soils, using laboratory tests (thermal needle probe technique), for future design and implementation of GEP systems in these soils.

2. Soils characterization

The needle probe tests were conducted on undisturbed and disturbed samples of Brazilian unsaturated soils. The disturbed samples were prepared at field moisture content and density.

The soil samples were obtained from two different sites in the São Paulo State, Brazil. In the first site, at São Carlos city, three different disturbed samples were tested: two samples of unsaturated colluvial soil (lateritic clayey sand) and one sample of residual sandstone soil (saprolitic clayey sand). The disturbed samples (re-compacted specimens) were extracted at different depths (3, 6 and 12 m). In the second site at Itirapina city, an undisturbed sample of unsaturated residual diabase soil (saprolitic sandy clayey silt) [11, 12] was collected from the depth of 8.3 m.

The soil of both sites present typical characteristics of unsaturated tropical soils. The mineralogical characterization of these soils indicates the presence of minerals such as, kaolinite, iron and alluminun oxides and hidroxides [13]. The chemical composition of the tested soils is illustrated in Table 1.

Table 1. Silica and oxides content of soil samples.

Soil type	Site	Percentage (%)		
		SiO_2	Fe_2O_3 and Al_2O_3	TiO_2
Colluvium at a depth of 3 m		60.9	31.2	2.1
Colluvium at a depth of 6 m	Site 1	58.6	33.7	2.3
Residual sandstone at a depth of 12 m		76.8	19.0	1.5
Residual diabase at a depth of 8.3 m	Site 2	27.2	53.6	6.0

Table 2 shows the results of soil characteristics of the Site 1 (obtained in [14, 15]) and of the Site 2 (studied in [11, 12]).

Table 2. Physical properties of the soil samples of Site 1 (remoulded) and Site 2 (intact) [11, 12, 14, 15].

Property	São Carlos site			Itirapina site
	Colluvium at 3 m	**Colluvium at 6 m**	**Residual sandstone at 12 m***	**Residual diabase at 8.3 m**
Sand content (%)	60.8	63.8	66.3	38.0
Silt content (%)	11.9	10.2	14.0	44.0
Clay content (%)	27.3	26.0	19.5	18.0
Unit weight (kN/m³)	14.2	17.1	19.6	15.0
Dry unit weight (kN/m³)	13.8	14.7	16.6	11.2
Particle unit weight (kN/m³)	27.1	27.0	27.0	29.1
Void ratio	0.96	0.84	0.63	1.6
Porosity (%)	48.9	45.6	38.6	62.0
Water content (%)	15.8	17.2	18.3	34.0
Saturation degree (%)	44.6	55.4	78.6	72.0
Liquid limit (%)	27.9	28.1	26.9	58.0
Plastic limit (%)	16.0	12.8	11.8	44.0

* field values obtained from intact samples at 9 m.

In the current study, the thermal needle probe tests were also performed on remoulded samples of Hostun fine sand (HN38) for comparison between the thermal properties of the tropical soils investigated with the ones of typical silica sand. The properties of Hostun sand are shown in Table 3.

Table 3. Properties of HN38 Hostun sand*.

Specific gravity of the sand particles	Gs	2.64
Maximum dry density: kg/m³	$\rho_{d(max)}$	1554
Minimum dry density: kg/m³	$\rho_{d(min)}$	1186
Average grain size: mm	d_{50}	0.12
Coefficient of uniformity	C_u	1.97

*tests results performed by Unisol Laboratories.

3. Needle probe tests

3.1. Test procedure

In the current work, for the thermal characterization of the specimens, a transient heat flux method was used, known as linear probe test or thermal needle probe test. This type of test consists in measuring the rate of temperature increase (ΔT) in a soil sample (or rock) over the time (t) using a heater powered by a constant power supply. The method is based on the theory assuming an infinitely narrow line source of heat and, in this case, the sample is considered as an infinite and homogeneous medium. All tests of this study were performed according to the ASTM standard method [16].

The equipment used was composed of a data logger, an electric voltage supply, and TP08 thermal probe fabricated by Hukseflux Thermal Sensors [17]. The probe is a stainless steel needle, with 70 mm long and diameter of 1.2 mm, instrumented with temperature sensors (thermocouple and thermistors) and a heating wire for the supply of thermal energy [16]. The TP-08 needle probe can be operated under a temperature range of 218.15 to 453.15 K, and has an accuracy of ± 3% + 0.032 (at 293.15 K) [17].

The probe was calibrated before each experiment using glycerol, a standard material with known thermal conductivity (λ = 0.286 W/mK at 289.15 K, according [16]). The calibration factor *C* was obtained from the ratio of the value of the thermal conductivity of the reference material to the measured thermal conductivity (Eq. (1)). Five calibration tests with glycerol were made to determine the average *C*-value.

$$C = \frac{\lambda_{material}}{\lambda_{measured}} \tag{1}$$

From the results of ΔT versus ln (*t*) (under heating condition), the values of thermal conductivity (λ) were determined by the thermal gradient related to the linear stage of the test, as recommended in [16], using Eq. (2):

$$\lambda = \frac{CQ}{4\pi\Delta T} \times \ln\left(t_2 - t_1\right) = \frac{CQ}{4\pi m} \tag{2}$$

being,

$$m = \frac{\ln\left(t_2 - t_1\right)}{\Delta T} \tag{3}$$

where *C* is the calibration factor (Eq. (1)), *Q* is the test power supply value (W), $(t_2 - t_1)$ is the considered time interval (s), ΔT is the temperature gradient (K) and m is the average linear gradient of the linear part the curve ΔT x ln (*t*).

According to the ASTM standard method used [16], if the needle probe has a diameter inferior to 2.54 mm the duration of the test should be from 30 to 60 seconds (heating phase) to ensure the accuracy of the result of thermal conductivity. For the type of needle probe used in this work (diameter inferior to 2.54 mm), the data of the first 10 to 30 seconds were ignored to ensure the accuracy of the results.

3.2. Preparation of soil specimens

The tests were performed on tropical soils samples (undisturbed and disturbed) and on HN38 Hostun silica sand samples, according to the ASTM standard method [16]. Thin-walled plastic tube samplers with 53.5 mm diameter and 200 mm height were used for preparation the soil specimens [16].

The remoulded specimens of colluvium and residual sandstone soils of the Site 1 were compacted to field density conditions (same moisture content and void ratio). The disturbed sample extracted at 12 m was compacted to the same density of an intact sample collected at 9 m in a previous investigation (presented in [14, 15]). For the preparation of the specimens for the needle probe tests, a predrilled hole was made (with a diameter smaller than that of the probe) to facilitate the installation of the probe into the remoulded soil. Additionally, a thin layer of thermal grease was applied on the surface of the probe to ensure a good contact between the soil and the probe [16].

For the silica sand specimens, the needle probe was placed in the center of the plastic sampler before the sand (Figure 1a). After that, the sand was placed in layers with density control using a vibration process (Figure 1b). The sand specimens were prepared using three different densities (dense, medium and loose sand) and two different moisture content conditions (dry specimens were moistened by capillarity, Figure 1c).

Two intact soil samples of the residual diabase soil of the Site 2 were prepared carefully by a manual process to ensure no changes of the natural physical properties. For the sample preparation, samplers of thin plastic tubes were used as shown in Figure 2. This figure also illustrates the details of the molding steps of the intact tropical soil specimens. Predrilled holes also were made to facilitate the installation of the probe into the specimens (thermal grease was also applied on the surface of the probe).

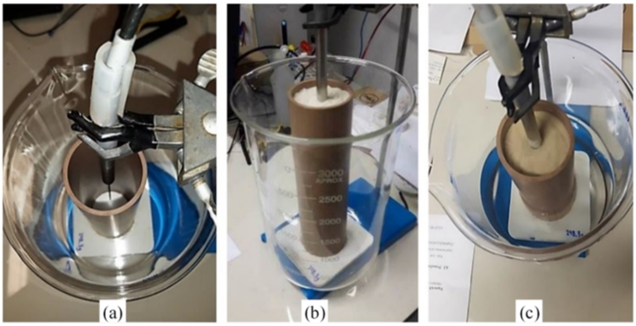

Figure 1. Preparation of the HN38 Hostun sand specimens: a) Needle probe installation, b) Dry specimen c) Wetting of the sand specimen by capillarity after test in dry condition.

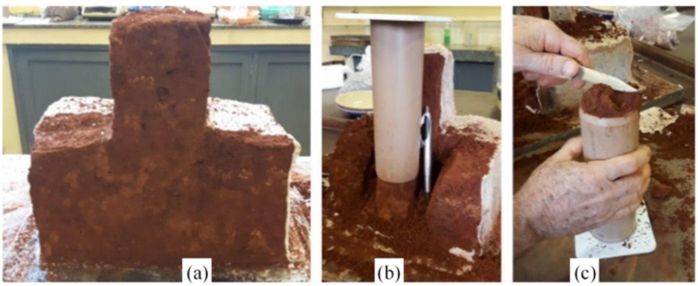

Figure 2. Preparation of the intact residual diabase specimens: a) undisturbed block sample of the tropical soil of the Site 2, b and c) manual carving process.

The physical properties of each specimen were calculated using the measurements of moisture content and unit weight (Table 4). The saprolitic soil of the Site 2 had a higher void ratio compared to the other specimens (2.5 times the value found for the sandstone residual soil of Site 1).

Table 4. Physical properties of the soil specimens.

Specimen	Sr (%)	e	γ_d (kN/m³)	γ (kN/m³)
Colluvium (unsaturated lateritic soil) at 3 m	47.84	0.85	14.37	16.52
Colluvium (unsaturated lateritic soil) at 6 m	47.85	0.76	14.77	16.80
Sandstone residual soil (unsaturated saprolitic soil) at 12 m	86.34	0.64	16.22	19.51
Unsaturated saprolite of diabase (sample 1)	57.83	1.69	10.61	14.17
Unsaturated saprolite of diabase (sample 2)	58.65	1.67	10.70	14.30
Loose HN38 sand (dry)	00.23	1.15	12.03	12.04
Loose HN38 sand (saturated)	99.39	0.99	13.01	17.87
Medium HN38 Sand (dry)	00.30	0.87	13.84	13.85
Medium HN38 Sand(saturated)	91.99	0.87	13.84	18.05
Dense HN38 Sand (dry)	00.32	0.82	14.21	14.22
Dense HN38 Sand (saturated)	88.13	0.82	14.21	18.12

4. Results

The duration of the tests was approximately 100 seconds. However, the analyses were made based on the data recorded during a period of 60 seconds (the first 10 seconds were ignored). Figure 3 shows the results of the tests performed on the HN38 sand specimens with different conditions of density (loose and dense) and moisture content (dry and saturated). This figure illustrates the significant effect of the moisture content on the specimen's temperature during the test.

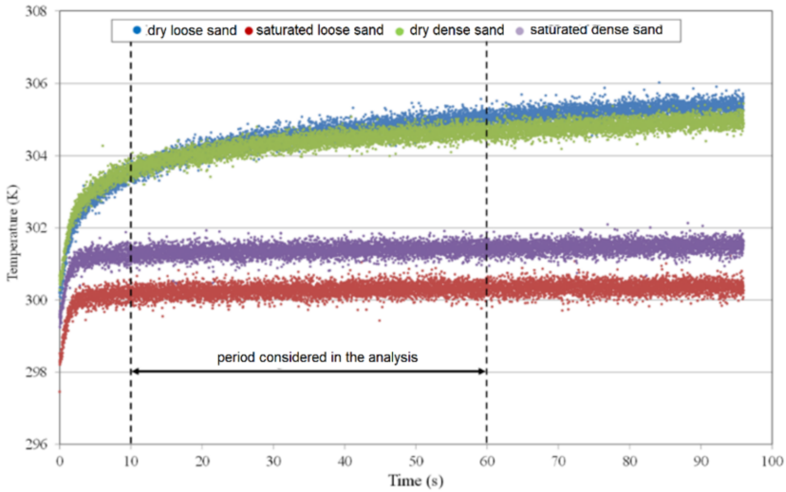

Figure 3. Results of thermal needle probe tests on samples of HN38 sand.

Figure 4 illustrates an example of temperature variation during the needle probe tests on the dense sand samples. The gradient of the straight-line section was used for the determination of the soil thermal conductivity using Eq. (2). Table 5 presents the results of thermal conductivity of all soil specimens tested in this study.

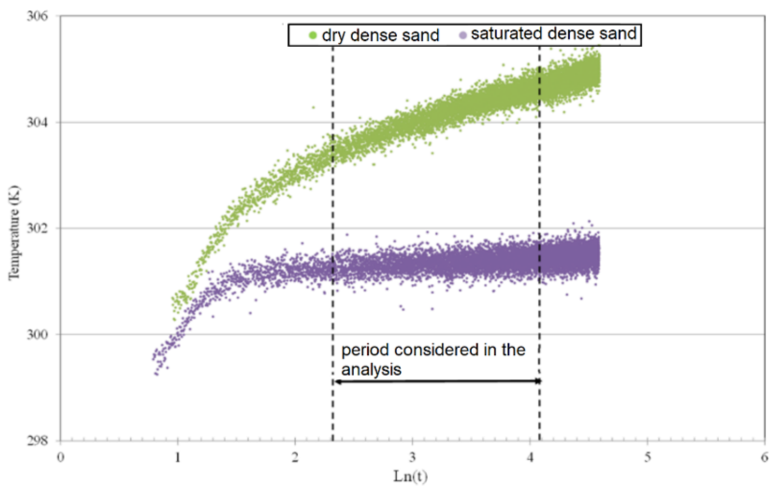

Figure 4. Results of temperature versus Ln (t) of the tests on HN38 sand specimens (dense dry and saturated).

The results of thermal conductivity of the sand specimens (varied from 0.20 to 0.27 W/mK for dry and from 1.6 to 2.41 W/mK for saturated sand) are in accordance with the previous results reported in the literature [18].

Figure 5 shows the curves of temperature versus Ln (*t*) of the tests performed on the specimens of the soil of the Site 1 (unsaturated lateritic and sandstone residual soils). The values of thermal conductivity of the soil specimens of Site 1 (sandstone residual soil) are higher than the values found for the intact specimens of the Site 2 (diabase rock residual soil) as illustrated in Table 5. This could be explained by the higher percentage of SiO_2 of the soils of the Site 1. However, the specimen of unsaturated diabase residual soil of the Site 2 has a much higher void ratio (of 1.6) compared to the soils specimens of the Site 1, that have an average void ratio value of 0.75 (Table 4).

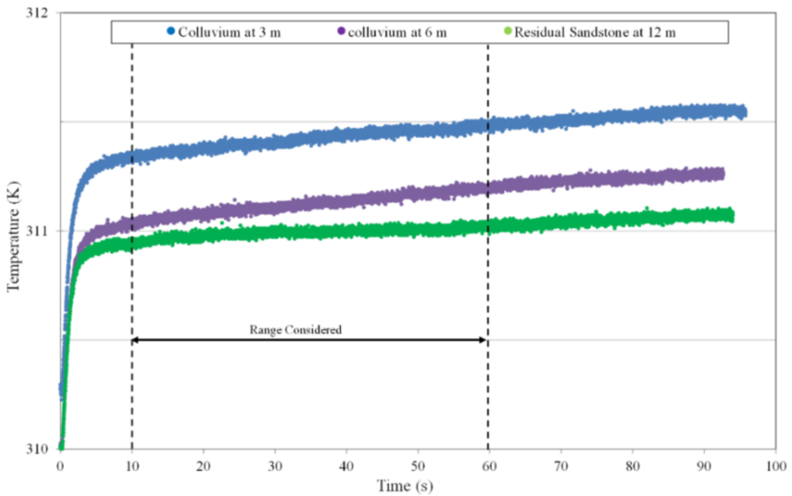

Figure 5. Results of temperature versus Ln (*t*) of the tests on the soil specimens of Site 1.

The thermal conductivity results indicated that the highly weathered unsaturated soils investigated, which have considerable percentage of iron and aluminum oxides, exhibited higher thermal conductivity values compared to the results obtained for the dry sand specimens, which have higher percentage of silica.

The current work is a preliminary study and further research is needed using different conditions of soil density and moisture content to evaluate the effect of the mineralogical composition on the thermal conductivity of weathered tropical soils.

Table 5. Results of soil thermal conductivity.

Specimen	Depth (m)	λ (W/mK)
Colluvium (unsaturated lateritic soil)	3	1.16
Colluvium (unsaturated lateritic soil)	6	1.08
Sandstone residual (unsaturated saprolitic soil)	12	1.66
Unsaturated saprolite of diabase soil (sample 1)	8.3	0.81
Unsaturated saprolite of diabase soil (sample 2)		0.98
Loose HN38 sand (dry)	-	0.20
Loose HN38 sand (saturated)		1.60
Medium HN38 Sand (dry)		0.24
Medium HN38 Sand(saturated)		1.94
Dense HN38 Sand (dry)		0.27
Dense HN38 Sand (saturated)		2.41

5. Conclusions

This paper presents the results of soil thermal conductivity of Brazilians unsaturated tropical soils for energy pile application. Thermal needle probe tests were conducted on soil specimens to quantify the thermal conductivity of lateritic and saprolitic soils of two different sites in Brazil, and of fine silica sand (HN38 sand) for comparison. The results illustrate the influence of the moisture content on the sand thermal conductivity and the possible effects of the mineralogical composition of tropical soils on the thermal properties.

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