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Thermal Properties of Mexico Basin Soils

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Abstract. Knowledge of soil thermal properties is essential for the design of many engineering projects such as municipal solid waste and radioactive waste disposal, oil and gas pipelines, and energy geostructures. There are many studies done on soil thermal properties around the world, however, the information about the thermal properties of Mexican soils is scarce. This paper presents the results of the thermal conductivity, volumetric heat capacity and thermal diffusivity of different soils of the Mexico Basin. Twenty-eight *in situ* and laboratory measurements were performed using a dual thermal needle at two different sites corresponding to the Lake and Hills Zone, respectively. The results show that the thermal properties of coarse-grained soils are within the ranges reported in the literature, whereas clayey formations present low thermal conductivities. This difference was attributed to the extremely high void ratios of the Mexico Basin clays.

Keywords. Thermal conductivity, Volumetric Heat Capacity, Thermal Diffusivity.

1. Introduction

Measurement of soil thermal properties is fundamental for many geotechnical applications such as energy geostructures, nuclear waste isolation, thermal ground improvement techniques, underground cable systems, oil and gas pipelines, and waste containment facilities [1]. Because of soil multi-phase nature, heat energy can be transported by different processes. However, conduction is generally the dominant mechanism. It occurs when thermal energy is transferred from one medium to another through particle contact and is described by Fourier's Law [2]. Accordingly, the main thermal properties are the thermal conductivity (λ), volumetric heat capacity (C_v) and thermal diffusivity (α), where $\alpha = \lambda / C_v$.

Despite their growing importance, there has not been a systematic characterization of the thermal properties of Mexican soils. There are different methods for evaluating soil thermal properties, including field and laboratory tests. Although the former evaluate larger volumes of soils under actual field conditions, they are costly, laborious and time-consuming. Conversely, laboratory tests are economical, relatively quick and allow controlling different boundary conditions, however they only provide local values of the parameters [3]. Thus, the assessment of a representative bulk value by laboratory methods requires many separate determinations to deal with the inherent soil heterogeneity [4, 5].

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This paper focuses on the experimental evaluation of the thermal conductivity λ, volumetric heat capacity C_v and thermal diffusivity α of soils from two different sites at the Mexico Basin. The main objective is to provide representative values of the thermal properties required for the design of the geotechnical applications detailed above.

2. Materials and methodology

2.1. Study sites

Twenty-eight measurements were performed at two different sites (Figure 1) at the Basin of Mexico: (1) Torre Bora building (TB1) in Santa Fe, CDMX; and (2) Former Lake Texcoco, in Texcoco de Mora, State of Mexico. At Texcoco site, two boreholes were analyzed herein referred to as TX1 and TX2.

The soil stratigraphy at the Torre Bora site was obtained from geotechnical investigations based on standard penetration tests (SPT). The site is located at the Hill Zone (Figure 1) according to the Mexico City Geotechnical Zoning [6] and consists of the following strata: (a) *Backfill material* (BF) composed of andesitic and pumice silty sand with gravel and boulders which extends up to 7.5 m deep; (b) *Blue Sands* (BLS), a 14 m layer of andesitic silty sand with gravel; (c) *Brown Tuff* (TF) extending up to a depth of 27 m; and (d) a layer of silty sand with gravel (SL) that extends to the end of the borehole. The groundwater level is below the sounding deep.

The soil stratigraphy at the Texcoco site corresponds to a typical Lacustrine Zone [3] and is mainly composed of soft clays and clayey silts interspersed with seams and layers of harder clayey silts with sands (Figure 1). The soil strata are: a) *Backfill of volcanic scoria* locally known as Tezontle of 0.65 m thick; b) *Upper Clay Formation* (UCF), a thick layer of very soft lacustrine clay interspersed with relatively thin seams of volcanic origin and sandy silt; c) *Hard Layer* (HL) composed of thin layers of hard sandy silt with variable cementation; d) *Lower Clay Formation* (LCF), a green brown clay interspersed with gray fat clay of the same origin of the UCF. The groundwater table is close to the surface between 0.5 and 1.15 m deep.

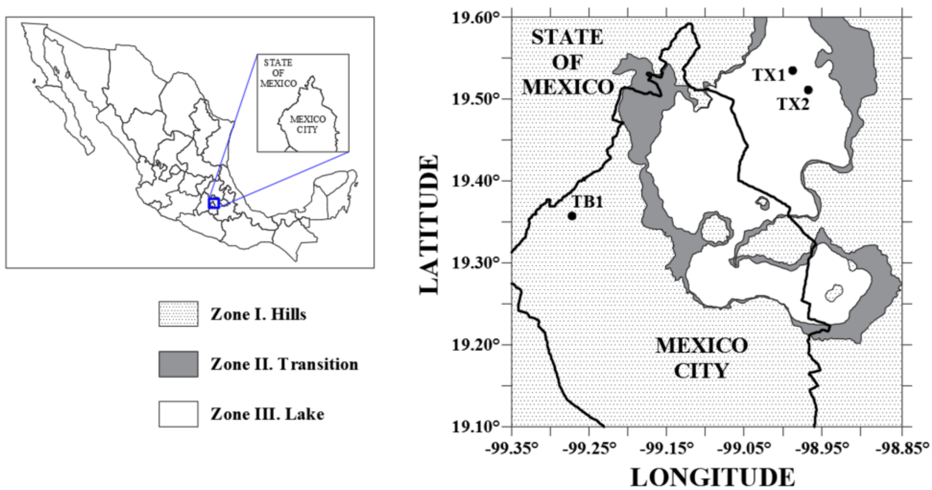

Figure 1. Overview of the study area and location of the field tests.

2.2. Thermal properties measurement method

A dual thermal needle [7] was used to measure the thermal properties (i.e. thermal conductivity, volumetric heat capacity, and thermal diffusivity) of the samples. It consists of two parallel stainless steel probes (30 mm long and 1.3 mm in diameter) spaced 6 mm apart. One of the needles contains a heater wire that supplies energy to the system, whereas the other encloses a thermocouple that measures the temperature changes caused by the heat transfer.

The interpretation method is based on the theory of temperature increase due to a heat pulse of finite duration injected into an infinite medium by a linear source. Thermal properties are obtained from an analysis of the temperature time series during the heating and recovery cycles. Bristow et al. [8] proposed the following equations to calculate α and C_v:

$$\alpha = \frac{r^2}{4}\left\{\frac{1/(t_m - t_0) - 1/t_m}{\ln\left[t_m/(t_m - t_0)\right]}\right\} \tag{1}$$

$$C_v = \frac{q'}{4\pi\alpha\Delta T_m}\left[E_i\left(\frac{-r^2}{4\alpha(t_m - t_0)}\right) - E_i\left(\frac{-r^2}{4\alpha t_m}\right)\right] \tag{2}$$

where r is the distance from the heat source, t_m is the time of maximum temperature change ΔT_m at r, t_o is the duration of the heat pulse, q' is the heat input, and $E_i(-x)$ is the exponential integral. This method has shown consistent results when compared to the parameters obtained by other standardized techniques [9].

In this study, the pulse width was 60 s and the heat input varied from 22 to 25 W/m. These values were selected to produce a temperature increase lower than 3°C and thus preventing coupled thermal moisture migration. Figure 2 shows typical measurements of temperature change at the sensor probe.

For coarse-grained soils (Zone I. Hills), *in situ* measurements were performed. A hole of 1.4 mm in diameter and 3 mm deep was drilled into each stratum. Prior to their insertion, the needles were coated with a thin layer of thermal grease (high-density ceramic polysynthetic thermal compound supplied by Arctic Silver) to ensure good thermal contact. For clayey soils (Zone III. Lake), undisturbed cylindrical samples (100 mm in diameter and 150 mm in height) were trimmed from Shelby tubes (geotechnical survey). In these cases, the soft consistency of the soil enabled inserting the needles by just pushing them into the specimen.

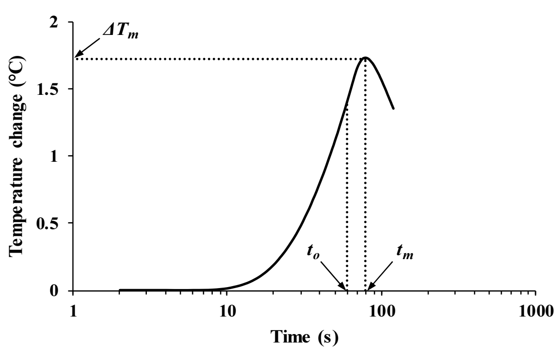

Figure 2. A typical temperature change vs time series for a coarse-grained soil (TB1 site).

3. Results and discussion

Figures 3 and 4 show the results of the thermal properties obtained from the Torre Bora building and Texcoco sites, respectively. Table 1 presents summary statistics for the strata of each geotechnical zone. For the TB1 sounding, the data shows that the four strata have similar thermal properties. Thermal conductivity varied from $\lambda = 0.661$ to 1.032 $Wm^{-1}K^{-1}$, volumetric heat capacity from $C_v = 1.128$ to 2.840 $MJm^{-3}K^{-1}$, and thermal diffusivity from $\alpha = 0.285$ to 0.761 mm^2s^{-1}. No specific trend with depth nor correlation with water content w was observed. These values are similar to those reported by [10] and [11] for partially saturated sands and silts.

Regarding the soundings TX1 and TX2, thermal conductivities ranged between $\lambda =$ 0.637 and 0.722 $Wm^{-1}K^{-1}$, volumetric heat capacity between $C_v = 1.558$ to 3.459 $MJm^{-3}K^{-1}$, and thermal diffusivity from $\alpha = 0.191$ to 0.464 mm^2s^{-1}. Compared to coarse-grained soils (TB1), the thermal properties of the clayey strata exhibited less dispersion with coefficient of variations equal to 3.6, 16.2 and 20.3 % for λ, C_v and α, respectively. Again, no specific trend with depth was observed. The measured thermal conductivity values were lower than those reported in the literature for saturated clays [10, 11]. These differences were attributed to the extremely high void ratios e of the Texcoco clays. As seen in Figure 4, e values ranged between 3.806 and 11.781, with an average of 7.221. Indeed, the measured thermal conductivities were similar to the thermal conductivity of water at 25°C (0.607 $Wm^{-1}K^{-1}$).

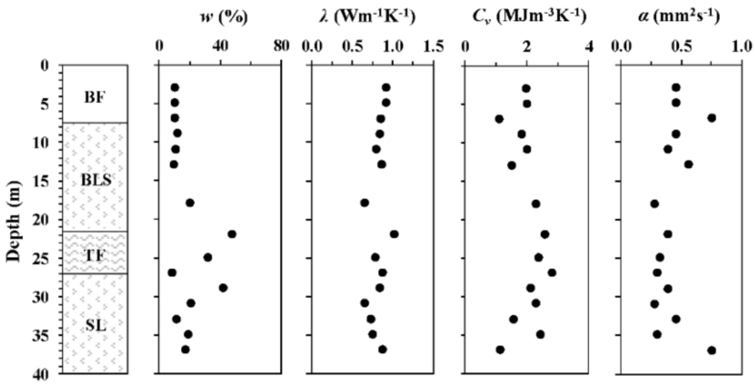

Figure 3. Stratigraphic profile and thermal properties at TB1 site.

Table 1. Measured values of thermal properties per Geotechnical Zone.

Soil unit	N	Thermal conductivity λ (W m^{-1} K^{-1})			Volumetric heat capacity C_v (MJ m^{-3} K^{-1})			Thermal diffusivity α (mm^2 s^{-1})		
		Min	*Max*	*Ave*	*Min*	*Max*	*Ave*	*Min*	*Max*	*Ave*
Zone I. Hills										
BF	3	0.858	0.934	0.906	1.128	2.013	1.712	0.464	0.761	0.563
BLS	4	0.661	0.878	0.799	1.543	2.319	1.933	0.285	0.569	0.429
TF	3	0.794	1.032	0.905	2.409	2.840	2.618	0.313	0.396	0.346
SL	5	0.660	0.880	0.798	1.156	2.456	2.085	0.285	0.761	0.422
Zone III. Lake										
UCF	10	0.637	0.707	0.682	2.000	3.459	2.970	0.191	0.349	0.236
LCF	2	0.712	0.722	0.717	1.558	1.796	1.677	0.396	0.464	0.430

Note: N= number of samples; *Min* = minimum; *Max* = maximum; *Ave* = average.

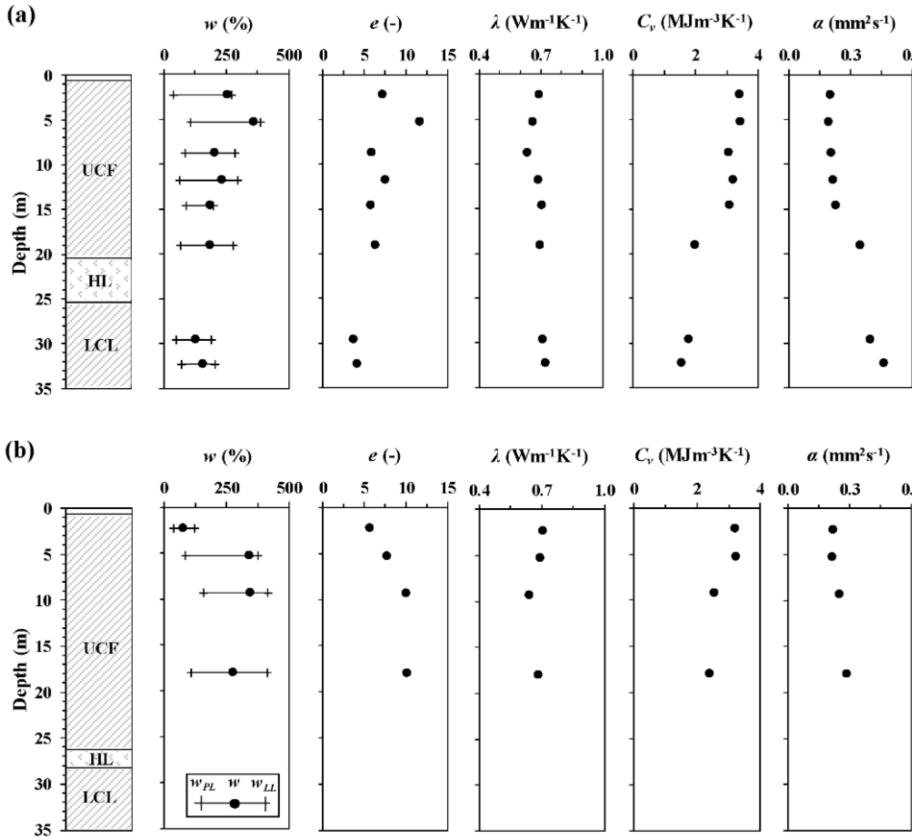

Figure 4. Stratigraphic profile and thermal properties at: (a) TX1 site, (b) TX2 site. Note: w_{PL} = plastic limit, w_{LL} = liquid limit.

4. Conclusions

Soil thermal properties are important parameters in many soil mechanics and geotechnical engineering projects associated with Energy Geotechnics. This paper described an *in situ* and laboratory study performed to characterize the thermal conductivity, volumetric heat capacity and thermal diffusivity of a set of representative soils of the Mexico Basin using a dual thermal needle. Although the mechanical properties of these deposits have been extensively studied in the past, the information about their thermal properties is scarce.

The properties of the coarse-grained soils (Zone I. Hills) were similar to those reported in the literature, whereas clayey formations (Zone III Lake) presented low thermal conductivities (between 0.637 and 0.722 $Wm^{-1}K^{-1}$). This was associated to the high void ratios of the clayey strata (7.221 in average). In general, the data present relatively low variations and no specific trend with depth.

The reported values represent an invaluable resource for the design of new technologies in the Mexico Basin, such as energy geostructures. However, new and more comprehensive geotechnical surveys are required to properly describe the soil thermal characteristics of the area.

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