THERMAL PROPERTIES AS A FUNCTION OF WATER CONTENT IN A SILTY POROUS MEDIA UNDER LABORATORY CONDITIONS

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1. Abstract

Soil thermal property data, especially as a function of water content, are currently not readily available. Demand for these data is, however, on the increase because of improvements in wider applications of soil heat and water transport models, as well as, of the vegetal growth studies. Most of these investigations were focused in sandy soils, clayed soils or peat horticultural substrates, due to the different properties and applications of each ones. Otherwise, in order to partly fill the thermal soil properties studies into other types of soils, we focused this work in the relation between thermal and hydraulic soil properties of a silty soil under laboratory conditions. Samples were obtained from Can Solé Road located in the Llobregat delta plain (NE of Spain), where frequently *Cynara scolymus* is cultivated. Small dual-needle sensors, employing the heat pulse methodology were used to measure the soil thermal diffusivity, specific heat capacity and thermal conductivity. One soil column with a specific design was used. The column was monitorized to determine the volumetric water content and matric potential, as well as, the thermal properties. To obtain these kinds of data a frequency domain probe and micro-tensiometer were used.

Preliminar results obtained up to now allow a rather complete understanding of the relation between thermal and hydraulic properties at laboratory scale of the silty soils. Preliminary distributed water content and thermal data allowed investigating the variability of these properties and its relations between them for this type of soils.

2. Introduction

Quantity and mostly quality of soil physical data are required in many field and laboratory experiments. These dataset are used for developing, testing and applying soil thermal properties (thermal conductivity and diffusivity and volumetric specific heat capacity) and water transport models. Soil thermal properties are influenced, among other variables, mostly for particle size distribution, water content and bulk density. The particle size and its distribution have an effect on the manner in which the moisture is held (Singh and Devid, 2000). Soil water content plays an important role in determining soil thermal properties, due the conduction through the soil is largely electrolytic (Van Rooyen and Winterkorn, 1957), thus when the soil moisture increase, then the thermal conductivity rise, because water (thermal conductivity equal to 0.57 $W \cdot m^{-1} \cdot K^{-1}$) is a good conductor (DeVries, 1963). Frequently, the statement is made that thermal properties of soils at the same moisture content for different textural class is highest in sand, intermediate in loam and lowest in clay. In the assumption that the water has a thermal conductivity 30 times as large as that the air to be refilling the pore space, therefore the thickness and the geometric arrangement of the water layer around the particles that conducts the heat from one soil grain to the other will have a high influence upon the heat conductivity of the system.

On the other hand, a soil with high bulk density will have a thermal conductivity and diffusivity higher than other with pore space available (due to the presence of air), where these thermal property will be reduced (Singh and Devid, 2000), having lesser effect if it compare with the moisture content (Al Nakshabandi and Kohnke, 1965).

In order to obtain accuracy and reliable in modelling results, a complete soil thermal properties dataset is needed. But sometimes, these dataset are incomplete. Looking for in the literature, can find that the most soil thermal properties experiences were performed using sand and clay textural class, also organic substrates (e.g. Hadas, 1973; Felipo et al., 1978; Bristow et al, 2001; Abu-Hamdeh, 2003). Thus, the aim of our work is divided in two operative objectives; **(i)** to evaluate a new soil column design to allow analyze the soil thermal properties and **(ii)** to relate the soil thermal properties for a silt loam textural class with a water content gradient under experimental control conditions.

3. Materials and Methods

Sampling plot was located in Can Solé Road, sited in the Llobregat delta plain (Northeast of Spain), where frequently there are *Cynara scolymus* crops. The samples were obtained between surface to 30 cm depth.

To characterize the soil of Can Solé Road the physical variables, particle size distribution (Psd), bulk density (BD), total organic carbon content (TOC), calcium carbonate content (CCC) and hygroscopic water content (Hw) were measured. Particle-size distribution was determined using the wetting sieve method for 2000 to 500 μm, and a device by dispersion laser beams (Malvern Mastersizer/E) for particles smaller than 500 μm. Bulk density and total porosity were determined from undisturbed sample volume. Total carbon content was analyzed by loss on ignition at 900ºC, and inorganic carbon content by loss on ignition at 200ºC, both using a Shimadzu SSM-5000A and solid sample module. These results we allowed calculate both contents TOC and CCC. Hygroscopic water content was determined by lost on weight after drying the samples at 105ºC during 24h.

Measurements of thermal-hydrodynamic properties were made on one soil column, constructed specifically for this experiment. Figure 1 shows the column one, which was developed in methacrylate component, with a inner slope of 3º allowing an enough drainage and to avoid the ponding processes in the device, and also a correct wetting process from the bottom of the column, which is connected to a separatory funnel (water deposit), that through the communicating vessel principle will allow both processes (drying and wetting)

The lower levels of the column were refilled with gravel (40 to 80 mm diameter) and sand particle size (250 to 1000 μm), both layers would allow to reach a necessary water level into the column and the homogeneity moisture of the sample, respectively. A separatory funnel provided a moderate matric potential gradient into the soil column, when was necessary to apply a suction gradient. Several sensors were placed for two different levels (**a** and **b**), allowing a control of two different moisture scenarios.

To determine the thermal properties one small dual-needle sensor (Decagon Devices Inc.) was employed. These kinds of sensors use the heat pulse methodology and yield reliable soil thermal diffusivity (**D**) and thermal conductivity (**k**) estimations, obtained by a non-linear least squares procedure during both processes (heating –eq. 1; and cooling –eq. 2), follow the equations:

$$\Delta T = -\frac{q}{4\pi k} Ei\left(\frac{-r^2}{4Dt}\right) \quad 0 < t \le t_1 \tag{1}$$

$$\Delta T = -\frac{q}{4\pi k}\left[-Ei\left(\frac{-r^2}{4Dt}\right) + Ei\left(\frac{-r^2}{4D(t-t_1)}\right)\right] \quad t > t_1 \tag{2}$$

Where, $\boldsymbol{q}$ is the rate of heat dissipation, $\boldsymbol{k}$ is the thermal conductivity, $\boldsymbol{Ei}$ is the exponential integral, $\boldsymbol{r}$ is the radius of the needle, $\boldsymbol{D}$ is the thermal diffusivity and $\boldsymbol{t}$ is time. Thermal properties were determined by fitting the time series temperature data during the heating and cooling processes of the dual needle.

The data were collected using a KD2-Pro reader-logger. To determine the volumetric water content ($\boldsymbol{\theta}$) and the matric potential (ψ), the soil column was monitorized with two EC-5 frequency domain probes (Decagon Devices Inc.) and two T-5 micro-tensiometer (UMS GmbH). The sensors were placed in couples (one T5 and one EC5 at the same level) for two different levels (**a** and **b**). A Campbell Scientific CR-850 and Decagon Devices EM-50 data-loggers were required to collect the data. The observed [$\boldsymbol{\theta}(\psi)$] data were fitted using van Genuchten equation (1980).

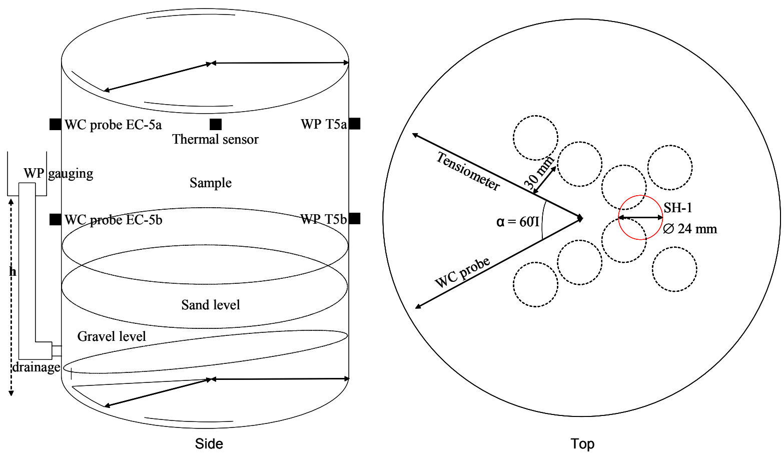

Figure 1 Side view and top view of the soil column scheme used to determine the soil thermal properties as a function of water content

4. Results

The studied soil from Can Solé Road was classified as silt loam textural class (USDA, 1975), with a particle size distribution for silt content always higher than 60%, mean sand content about 34%, and mean clay content about 4%. Mean bulk density is 1.47 $g \cdot cm^{-3}$ and total porosity 45%. Mean total organic carbon content was about 3.1%, mean calcium carbonate content was 40.3%.

Soil water retention curve (Figure 2) was obtained fitting the observed data to the Van Genuchten model. For these, the RETC code (Van Genuchten et al., 1991) was performed, thus obtaining the hydraulic parameters of the model (θs, α and N). For θr parameter the mean HW value (in $cm^3 \cdot cm^{-3}$) was used. Water retention curve showed a volumetric water content close to saturation about 0.46 $cm^3 \cdot cm^{-3}$. The values of water content at field capacity and at permanent wilting point were 0.25 and 0.06 $cm^3 \cdot cm^{-3}$ respectively. The van Genuchten model (1980) fitted acceptably the estimated water retention data to observed data with $r \cong 0.98$ and $p \leq 0.01$. Estimated water content values are in the range of the found in the literature for these types of soils (Cameron, 1978; Gupta and Larson, 1979; Martínez-Fernández et al., 2003).

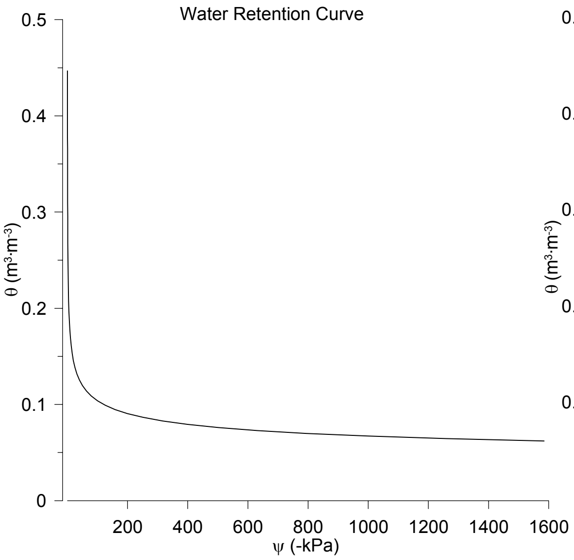

Figure 2 Estimate soil water characteristic curve for the studied silty loam soil

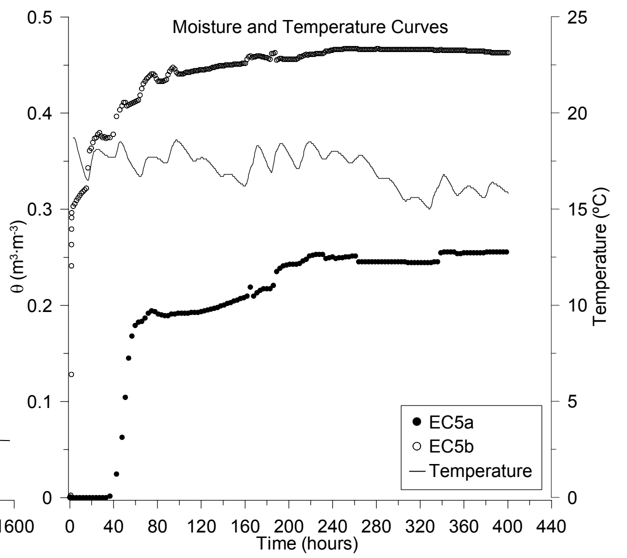

Figure 3 Soil wetting process and temperature cicle for the studied soil

Soil wetting curves are presented in Figure 3. The two curves showed a well-defined wetting process that was determined by the two EC-5 probes. The capillarity rise between the **a** and **b** points (12 cm long) were spent 40 hours, with differences in the water content between **a** and **b** levels, when the probe **a** (upper level) started to increase the moisture values (from 0 initial) about 35%. These differences decreased to 20% when the probe **b** (lower level) reached at saturation, and then reaching both levels the near steady-state conditions. In this point, the observed matric potential data was -1.41 kPa for level **a**, and close to 0 kPa for level **b**.

Figure 4, shows the influence of water content in the thermal properties for a silty loam soil. Thermal conductivity (Fig. 3A) and thermal diffusivity (Fig. 3B) have been plotted *versus* volumetric water content, just that these two porperties were directly observed data. Whereas, thermal resistivity was calculated as a inverse of thermal conductivity and volumetric specific heat as a function of **k** and **D**. For this reason its have not been showed here.

In Figure 4A, can observe that for a silt loam soil the **k** showed a gradual increase insofar water content increased (Singh and Devid, 2000), presenting a strong reaction when soil moisture was over 20% $vol \cdot vol^{-1}$, therefore, the greatest increase in **k** occurs in the wetting range. Similar results were showed by Al Nakshabandi and Kohnke (1964) with the same type of soil textural class. Another interesting fact was that, both thermal properties (**k** and **D**) showed a nearby steady-state scenario when the volumetric water content was close to 25% $vol \cdot vol^{-1}$.

Figure 4B, shows the thermal diffusivity and its relation with soil water content. Thermal diffusivity showed a similar behaviour than thermal conductivity, both due to severe vapour transfer before to react with high soil moisture, i.e. the fast increase of the **D** values between 10% and 20% $vol \cdot vol^{-1}$ of water content.

The **D** property as a direct observe data, presented an excellent relationship with volumetric water content. To fit the curve, to the observed data, a third degree polynomial was used. Estimated data fitted very acceptably to observed data, with $r \geq 0.99$ for $p \leq 0.01$. Thus, the thermal diffusivity could be a optimum water content predictor based on a fast, economic and accurate thermal property measurement as is the thermal diffusivity.

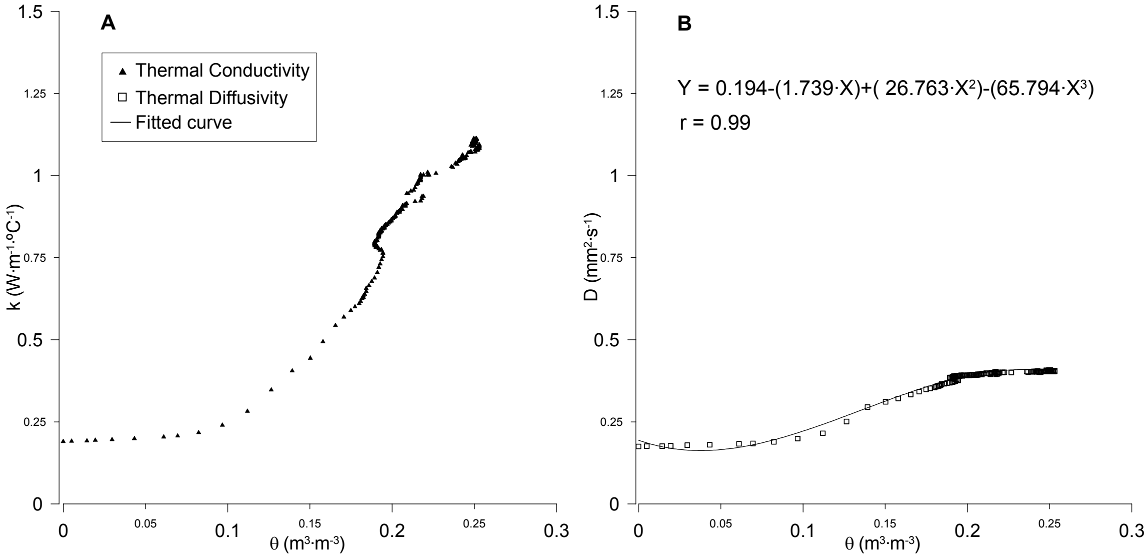

Figure 4 A: Relation between soil thermal conductivity (k) and volumetric water content. B: Relation between soil thermal diffusivity (D) and volumetric water content, and fitted curve

5. Conclusions

As a summary of theses preliminary results, silty loam soil presented a well-defined wetting process, yielding a well gauge for the thermal and hydrodynamic data collected. A slow capillary rise in the porous media favoured a not collapse of the porosity by the air-entry, and therefore a direct contact between the thermal sensors and soil. Thermal properties showed a well realtionship with water content, being directly proportional the increase of water content values with the increase of the measured thermal conductivity and diffusivity. Thermal diffusivity data fitted well to a third degree polynomial curve, and therefore could be a good predictor for the soil moisture, eventhough still need a further research.

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