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Clay–Loam soil thermal properties survey

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ABSTRACT

The effect moisture content (10-25% wet basis) and bulk density (1350-1550 kg/m^3) on the thermal properties of clay – loam soil was investigated through laboratory studies. These laboratory experiments used the single probe method to determine thermal properties. For the clay–loam soils studied, thermal properties increased with increasing soil density and moisture content ($P \leq 0.05$). The thermal conductivity and thermal diffusivity of clay–loam soil ranged from 0.365 to 0.791 W/m K and 2.71×10^{-7} to 4.81×10^{-7} m^2/s, respectably. However, the effect of bulk density on increasing the thermal properties is more than that of moisture content. Regression equations were established which could be used to reasonably estimate the values of the thermal conductivity and thermal diffusivity as a function of specified moisture content and bulk density.

1. Introduction

Soil thermal properties are required in many areas of engineering, agronomy, and soil science. In agronomic practice, seed germination, seedling emergence and establishment are affected by their microclimate, which is influenced by soil thermal properties (Ekwue *et al*., 2006; Danelichen *et al*., 2013). The study of temperature distribution in soil profiles requires a solution of the heat transfer equation. This solution depends on the formulation of the boundary condition as well as the soil thermal properties, which are represented by the thermal conductivity and thermal diffusivity coefficients (Gnatowski, 2009).

Thermal conductivity is the ratio of heat flux density to temperature gradient in a material. It measures the ability of a substance to conduct heat. Also, thermal diffusivity is the ratio of the thermal conductivity to the heat capacity of a material (Huang and Liu, 2009). It is a parameter that quantifies the ability of a material to store thermal energy during heat transfer processes. Thermal diffusivity is the controlling thermal property during transient conductive heating processes.

The literature contains many reports the effect of moisture content, bulk density, temperature, tillage treatments, salt Concentration, and organic matter on thermal properties of soils (Edem *et al.,* 2012; Usowicz *et al.,* 2013; Xiaodan *et al.,* 2009; Ekwue *et al.,* 2006; Dec *et al.,* 2009; Anandakumar *et al.,* 2001; Ludynia and Orman, 2013; Usowicz *et al.,* 2013; Abu-Hamdeh and Reeder, 2000). But, for Iranian soils information on thermal properties is lacking. These data are needed for constructing models to predict soil thermal regimes. Such information assumes greater importance with increasing attention being paid to developing the agricultural industry in Iran. Therefore the objective of this study is to determine apparent thermal conductivity and thermal diffusivity values for clay – loam soil as a function of moisture content and bulk density.

2. Theory of operation

The single probe methodology is based on a solution of the heat conduction equation for a line heat source in a homogenous and isotropic medium at a uniform initial temperature. The equation for radial heat conduction can be represented as (Fontana *et al*., 2001):

$$\frac{\partial T}{\partial t} = \propto \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{2r} \frac{\partial T}{\partial r} \right) \qquad (1)$$

where T is temperature (°C), t is time (s), α is thermal diffusivity (m2/s), and r is radial distance

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(m). The solution to equation (1) is (Aghbashlo et al., 2008; Opoku et al., 2006):

$$\mathrm{T}-\mathrm{T}_0=-\left(\frac{\mathrm{Q}}{4\pi \mathrm{k}}\right)\mathrm{Ei}\left(-\frac{\mathrm{r}^2}{4\alpha \mathrm{t}}\right) \qquad (2)$$

where Q is the heat produced per unit length per unit time (W/m), k is the thermal conductivity of the medium (W/m ºC), T_0 is initial temperature of soil (ºC), and Ei(-x) is An exponential integral function. The heat input of line heat source can be calculated using:

$$\mathrm{Q}=\mathrm{I}^2\mathrm{R} \qquad (3)$$

where I is the current (A) and R is the resistance of the heat wire per unit length (Ω/m). The equation (2) can be restated as (Fontana *et al.*, 2001; Opoku *et al.*, 2006):

$$\mathrm{T}-\mathrm{T}_0=\frac{\mathrm{Q}}{4\pi \mathrm{k}}\left(\ln\left(\frac{4\alpha \mathrm{t}}{\mathrm{r}^2}\right)-\gamma-\left(\frac{\mathrm{r}^2}{4\alpha}\right)-\frac{(-1)^2}{2.2!}\left(\frac{\mathrm{r}^2}{4\alpha}\right)^2 - \cdots - \frac{(-1)^{\mathrm{n}}}{\mathrm{n.n!}}\left(\frac{\mathrm{r}^2}{4\alpha}\right)^{\mathrm{n}}\right) \qquad (4)$$

where γ is Euler's constant (0.5772). For small values of $r^2/4\alpha t$, all terms after the second one at the right hand side of the equation (4) would be negligible. Thus, the equation (4) can be expressed as (Ekwue *et al.,* 2006; Fontana *et al.,* 2001):

$$\mathrm{T}-\mathrm{T}_0=-\left(\frac{\mathrm{Q}}{4\pi \mathrm{k}}\right)\left(\ln(\mathrm{t})-\gamma-\ln\left(\frac{\mathrm{r}^2}{4\alpha}\right)\right) \qquad (5)$$

Equation (6) means that the gradient of a plot of (ΔT) versus natural logarithm of time [Ln(t)] is equal to S = Q/(4πk). The thermal conductivity can then be calculated as:

$$\mathrm{k}=\frac{\mathrm{q}}{4\pi \mathrm{S}} \qquad (6)$$

Based on equation (5), the intersection of the regression line with the t axis (ΔT = 0) gives (Fontana et al., 2001):

$$\ln(\mathrm{t}_0)=\gamma+\ln\left(\frac{\mathrm{r}^2}{4\alpha}\right) \qquad (7)$$

Thus;

$$\alpha=\frac{\mathrm{r}^2}{2.246\ \mathrm{t}_0} \qquad (8)$$

3. Materials and methods

3.1. Probe details

The line heat source probe method used for the determination of thermal properties simultaneously (Fig. 1a). The probe, which is 90 mm long and 6 mm in diameter, consists of a heater wire of resistance 30.4 Ω/m (Fig. 1b). The space between the heating element and the stainless steel tube is filled with thermal epoxy, which provides excellent thermal conduction and acts as an electrically insulated material. The temperature of the probe can be determined with the help of a Type-K thermocouple, which is attached to its surface. The sample holder has a PTF cylinder with an inner diameter of 50 mm, a length of 150 mm with a movable piston (for compression of soil samples) to examine the effects of compaction on thermal properties.

To determine the bulk thermal properties of soil, samples at the desired moisture content and temperature were tightly packed inside the sample holder and compaction was done by movable piston. The tightly filled sample was weighed by digital balance (A&D GF600, Japan) and recorded. The bulk density of the sample in the sample holder was calculated by the ratio of mass to volume. Following this, the probe was inserted through the center of the sample. Then the sample holder was placed in a water bath in order to heat it to the desired temperature. As soon as a constant temperature of the thermocouples was reached, a constant DC voltage was applied from the power supplier, resulting in a constant electric current through the heating wire. A digital multi-meter was used to monitor the current. The thermocouple temperatures were recorded by the data logger every second for 3 min. After one replication, the probe was cooled to the initial temperature before the next replication began.

3.2 Soil samples

The clay loam soil representing major agricultural soils in Arak, Iran was selected. The soil samples (24.5±3.1% sand, 36.7±4.4% silt, and 38.8±3.5% clay) were collected horizontally from the top layer (5 to 15 cm) of soil profile located at the Arak Branch, Islamic Azad University agricultural farm, Arak, Iran. Soil particle size distribution was determined using the hydrometer method. Soil had an initial moisture content of 20.8 ± 0.5% wet basis, which was determined by using a standard oven method at 105 ºC for 24 h (Ekwue *et al.,* 2011). The moist soil samples was dried in a hot air oven at 70°C to get the desired moisture content of 15%, 10% and 5% wet basis. Each dried soil sample was kept in a plastic box which was sealed by plastic film to prevent moisture loss. Then it was refrigerated at 5°C for at least 24 h to allow moisture in the samples to equilibrate before analysis. Finally, moisture content of the sample was checked again before use to ensure it was at the correct level.

3.3. Statistical analysis

The experiments are carried out at three replications and the mean values of data are reported with standard deviation. An analysis of variance was conducted at 0.01 confidence level to examine the effect of temperature, moisture content and density on the thermal diffusivity. The statistical evaluation was performed by using SPSS software Ver.18. Also, the coefficient of determination (R^2) and standard error of the residuals (SER) were calculated to evaluate the fitting of mathematical relationships to experimental data.

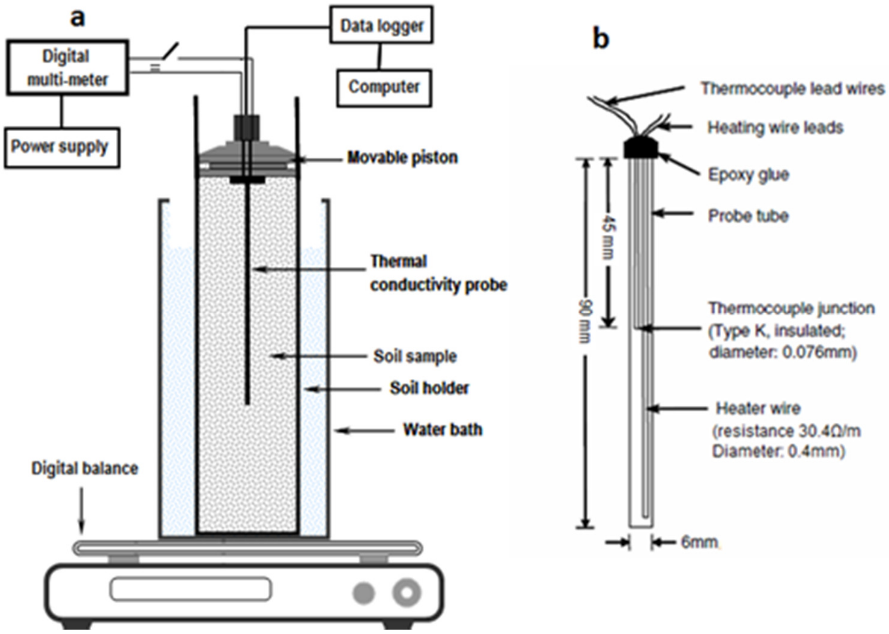

Fig. 1: Schematic diagram of the experimental set-up (a) and thermal conductivity probe (b)

4. Results and discussion

4.1. Thermal conductivity

The measured values of thermal conductivity with various moisture contents and bulk densities of clay–loam soil are presented in Fig. 2. It was found that thermal conductivity of soil samples increased with an increase in moisture content and bulk density ($P \leq 0.05$), which was in agreement with some previous researchers who studied thermal conductivity of other soils (Evett *et al.,* 2012; Gnatowski, 2009; Ekwue *et al.,* 2011; Xiaodan *et al.,* 2009).This may be due to the fact that the thermal conductivity of water ranges from 0.6106 to 0.6372 W/m K at temperatures of 26.5-45°C (Mahmoodi and Kianmehr, 2008) which is much higher than that of air filled in pores following reduction in moisture. Regarding the effect of the pore of air is a poor heat conductor and has very low thermal conductivity, about 0.0272 W/m K at about 38°C, as compared to the solid particles of soil sample and moisture. Therefore as the bulk density increased, the volume of pores reduced resulting in a higher thermal conductivity value of samples (Evett *et al.,* 2012; Kantrong *et al.,* 2009; Ekwue *et al.,* 2011; Abu-Hamdeh and Reeder, 2000). The measured values of the thermal conductivity of the clay–loam soil are varying between 0.365 to approximately 0.791 (W/m K). Thermal conductivity values reported here lie well within the range 0.15–0.79 W/m K for loam soil as given by Ghauman and Lal (1985).

Investigations of Ekwue *et al.* (2006) showed that the thermal conductivity of compacted Trinidadian soils increased from 0.4 to 2 W/m K in the moisture range of 15-50% wet basis, bulk density range of 800 to 1900 kg/m^3 and 0-12% peat content. Abu-Hamdeh (2000) research works showed that the thermal conductivity of the Jordanian clay loam and loam soils increased linearly from 0.3 to 0.8 W/m K with moisture increase in the range of 9-18% wet basis. Also, he found that the soil tillage significantly reduced thermal conductivity ($P \leq 0.01$) for both soils. Abu-Hamdeh and Reeder (2000) investigations showed that the thermal conductivity increased from 0.58 to 1.94 W/m K for sand, 0.19 to 1.12 W/m K for sandy loam, 0.29 to 0.76 W/m K for loam, and 0.36 to 0.69 W/m K for clay loam soil at densities from 1230 to 1590 kg/m^3 and moisture contents from 1.4 to 21.2% wet basis. The thermal conductivity of sandy loam, clay loam and clay soils increased from 0.9 to 1.55 W/m K (for filed condition) and 0.5 to 2 W/m K (for laboratory-compacted condition) with increase in bulk density from 1000 to 2000 kg/m^3 and moisture content from 5 to 40% wet basis (Ekwue *et al.*, 2011). Edem *et al.*, (2012) reported that the trend of thermal conductivity for different soils followed the order of sand > loam > clay > black earth (soil from dump site). Anandakumar *et al.,* (2001) found that the thermal conductivity of sandy–clay soil increased from 0.518 to 2.148 W/m K with increase in moisture content and temperature. Dec *et al.*,

(2009) studies revealed that the thermal conductivity of rough rice increased from 0.9 to 0.106 W/m K in the temperature range of 19-32°C and moisture content range of 23-40% wet basis.

Also, to evaluate the individual effect of independent variables on the thermal conductivity, analysis of variance (ANOVA) table was constructed as shown in Table 1. Comparing F-values of the moisture content and bulk density showed that the effect of bulk density on the thermal conductivity was higher (high F-value) than the effect of moisture content (low F-value). The relationship between thermal conductivity, moisture content and bulk density of soil can be described by the following regression model.

$$k = -20.33 + 0.0273M_c - 4.5343 \times 10^{-5}M_c - 1.245 \times 10^{-5}M_c\,\rho_b + 0.0272\rho_b - 8.829 \times 10^{-6}\rho_b^2 \qquad (9)$$

where k is the thermal conductivity (W/m K), M is the moisture content (%, wet basis) and ρ_b is the bulk density (kg/m^3). The R^2 and SER were 0.974 and 0.0172, respectively. This indicates that equation (9) represented satisfactorily the thermal conductivity data of clay–loam soil in the bulk density and moisture content ranges tested in this study. The relationship between these measured physical properties is statistically significant and can be expressed in the form of (Gnatowski, 2009):

$$k = a + b\exp\left(-\frac{C}{M_c}\right) \qquad (10)$$

where a parameter which expresses the thermal conductivity at T = o, b and C are the shape parameters (W/m K). This equation is a special case of the Campbell model where famous model to prediction of thermal conductivity of soil (Ekwue *et al.,* 2006; Evett *et al.* 2012). The optimization procedure leads to the following values of parameters: $a = -3.74\times10^{-3}\,\rho_b$, $b = 6.91\times10^{-4}\,\rho_b^{1.25}$, C = 0.312, R^2 = 0.901 and SER = 0.0321.

Table 1: Analysis of variance (ANOVA) for effect of moisture content and bulk density on thermal conductivity of clay–loam soil

Source	df	Mean Square	F_{cul} –value	Sig.
Regression	26	0.019	75.244*	0.000
ρ_b	7	0.057	225.64*	0.000
M_c	3	0.040	156.34*	0.000
$\rho_b \times M_c$	16	0.001	3.308*	0.001
Error	54	0.000		
Total	81			

*Highly significant

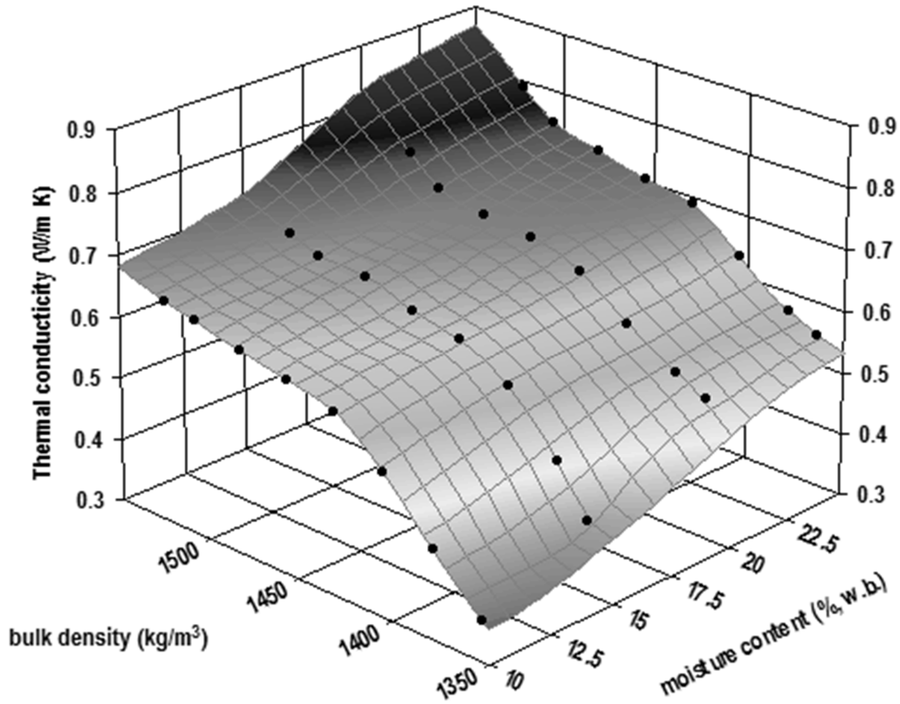

Fig. 2: Influence of moisture content and bulk density on thermal conductivity

4.2. Thermal diffusivity

Variation of thermal diffusivity clay–loam soil samples as a function of moisture content and bulk density is shown in Fig. 3. The thermal diffusivity values of soil samples were varied in the range of

2.71×10^{-7} to 4.81×10^{-7} m^2/s. The increased thermal conductivity with increasing moisture content might be due to higher thermal conductivity of water compared to the dry material of sample associated with air-filled pores. Initially, thermal diffusivity increased rapidly with an increase in bulk density for soil samples (for low moisture content 10-15% wet basis). However, further increases in bulk density increased the volumetric heat capacity only slightly.

Dec *et al.,* (2009) showed that the values of thermal diffusivity under conventional tillage treatment were greater than under conservational and varied between 3.60×10^{-7} – 4.4×10^{-7} m^2/s. The value of soil thermal diffusivity depends highly on quartz content (Robertson, 1988). Souza *et al.,* (2006) reported that thermal diffusivity of forest soils of Brazil ranged from 1.45×10^{-7} to 6.74×10^{-7} m^2/s and thermal diffusivities during the rainy period were significantly smaller than during the dry period. Nwadibia *et al.,* (2010) reported that the thermal diffusivity of clay soil varied from 1.08×10^{-3} to 0.1178 m^2/s at 1200 - 1350 ºC temperature. Danelichen *et al*., (2013) showed in the observed water content range (15-45%), the average thermal diffusivity was 1.95×10^{-7} m^2/s in the top layer (0.01-0.15 m) and 1.02×10^{-7} m^2/s in the subsurface layer (0.01-0.30 m). Also, Gnatowski (2009) reported that thermal diffusivity of organic topsoil layer varied between 1.3×10^{-7} to 2.5×10^{-7} m^2/s at 0-90% moisture content. The results show that thermal diffusivity of soils (Southwestern Nigeria) range from $3.46–7.52\times10^{-7}$ m^2/s at 13.0–16.2% moisture content, 1725–1930 Kg/m^3 dry density and 28.9–35.4 ºC temperature (Oladunjoye and Sanuade, 2012).

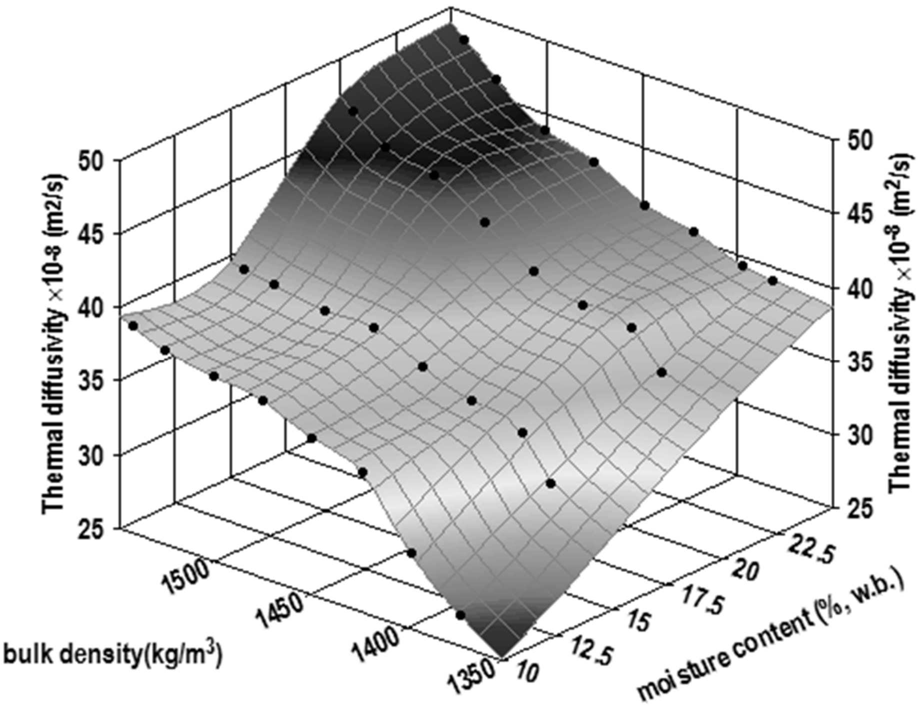

Fig. 3: Thermal diffusivities as a function of moisture content and bulk density for clay–loam soil

Equation (11) shows the effect of moisture content and bulk density on thermal diffusivity of the soil samples with following coefficients:

$$\alpha = [-353.845 + 0.594\mathrm{M_c} + 0.470\rho_b - 1.423 \times 10^{-4}\rho_b^2] \times 10^{-8} \qquad \begin{array}{l} R^2 = 0.932 \\ SER = 1.267 \end{array} \qquad (11)$$

where α is the thermal diffusivity (m^2/s), M_c is the moisture content (%, wet basis) and ρ_b is the bulk density of soil sample (kg/m^3).

Conclusion

Results of this investigation clearly showed significant variation in thermal conductivity of sunflower seeds with changing moisture content and bulk density. The thermal conductivity and thermal diffusivity increased from 0.365 to 0.791 W/m K and 2.71×10^{-7} to 4.81×10^{-7} m^2/s, respectably within the range of input variables studied. The effect of the bulk density on increasing the thermal properties of clay–loam soil was more than that of moisture content.

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