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A comparison of two methods used to evaluate thermal conductivity for some soils

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Abstract

The effect of bulk density and moisture content on the thermal conductivity of some Jordanian soils was investigated through laboratory studies. The soils used were classified as sand, sandy loam, loam, and clay loam. The hot wire method was used to perform the experiments. Heating and cooling methods were used to evaluate thermal conductivity for the soil types and the results obtained by the two methods were compared. Thermal conductivity increased with increasing soil density and moisture content. It was found that the soil containing higher percentage of clay particles had lower thermal conductivity. Graphical comparisons of thermal conductivity obtained by both methods, cooling and heating, for each soil type are presented. In general, the heating data yielded thermal conductivities that were slightly higher than those derived from the cooling data. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Thermal conductivity is considered one of the most important thermal properties of plant environment. It is considered as the property that controls heat flow through materials of different types.

Thermal conductivity of soil is affected by several factors. Some of these factors are inherent to the soil itself such as the organic matter of the soil. In the natural state of the soil, the organic matter content is relatively fixed because it is in relative equilibrium with the biologic activity occurring in the soil. Other factors influencing the thermal conductivity of soil can be managed externally. Bulk density and moisture content are some of these controlled factors.

Thermal properties of soil affect the microclimate around the plant, and hence affecting the plant itself. Germination, plant growth and crop development are all dependent on soil thermal properties. In recent years, considerable efforts have gone into developing techniques to determine these properties. A certain soil will not necessarily have a given value of thermal conductivity unless all of the factors are approximately the same whenever the measurements are taken.

Thermal properties are determined indirectly by measuring the rise or fall of temperature in response to heat input to a line source at the point of interest [5]. Models were developed that allow estimation of thermal conductivity and volumetric heat capacity of soils from the volume fractions of their constituents and the shape of the soil particles [3]. The dual-probe heat-pulse technique [1,2] has been used to make measurements of soil thermal properties. It consists of two parallel needle probes separated by a distance (r). One probe contains a heater and the other a temperature sensor. With the dual-probe device inserted in the soil, a heat pulse is applied to the heater and the temperature at the sensor probe is recorded as a function of time. In a study of thermal conductivity and thermal diffusivity of Nigerian soils, Ghauman and Lal [4] found that thermal conductivity increased with increasing soil moisture content.

The hot wire method was used to measure the thermal conductivity of the soils in this study. In this method, an electrical wire is implanted in the experimental soil sample. A steady current is supplied to the

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electrical wire and the temperature rise and fall of the heating wire is measured by a thermocouple and recorded during a short heating and cooling interval. Due to the linear heat source and cylindrical geometry of these heat-dissipation sensors, sensor temperature (T) during heating should be related to time (t) according to the theoretical solution for a line heat source [1,3,4]

$$T - T_0 = (q'/4\pi\rho c\lambda)\ln(t + t_0) + d, \quad (1)$$

where T_0 is the initial temperature (°C), q' the energy input per unit length of heater per unit time (W m^{-1}), ρc and λ the volumetric heat capacity (J m^{-3} $°C^{-1}$) and thermal diffusivity (m^2 s^{-1}), respectively, of the material surrounding the line source, t_0 the time correction used to account for the finite dimensions of the heat source and the contact resistance between the heat source and the medium outside the source, and d is a constant. The corresponding equation for sensor temperature during cooling after t_h seconds of heating is given by

$$T - T_0 = (q'/4\pi\rho c\lambda)[\ln(t + t_0) - \ln(t + t_0 - t_h)] + d, \quad (2)$$

Eq. (1) can be used to obtain the thermal conductivity, k (W m^{-1} $°C^{-1}$), since by definition

$$k = \lambda\rho c. \quad (3)$$

Nonlinear least-squares regression is used to solve for k; however, this requires significant data storage and numerical processing. An alternative approach is to assume $t_0 \ll t$ so that $\ln(t + t_0)$ approximately equals ln(t). With this assumption, linear regression can be used to calculate k from heating data with Eq. (1) and ln(t) as the independent variable or from cooling data with Eq. (2) and $\ln[t/(t - t_h)]$ as the independent variable. Furthermore, if the relation between T and ln(t) is smooth, then k can be simply estimated from the change in sensor temperature between two times, t_1 and t_2, by

$$k = (q'/4\pi)[\ln(t_2) - \ln(t_1)]/[T(t_2) - T(t_1)]. \quad (4)$$

For cooling, the analogous equation to Eq. (4) is

$$k = (q'/4\pi)\ln[(t_2/t_1)(t_1 - t_h)/(t_2 - t_h)]/[T(t_2) - T(t_2)]. \quad (5)$$

Eqs. (4) and (5) can be represented in electrical form by substituting I^2R for q'

$$k = 0.0796 I^2 R/S, \quad (6)$$

where k is the thermal conductivity (W m^{-1} K), I the current in the line source (A), R the specific resistance of the wire (Ω m^{-1}), and S is the slope of the straight-line portion of the temperature rise versus ln(t) during heating process (i.e., $S = \Delta T/\Delta\ln(t)$) and S is the slope of the straight-line portion of the temperature fall versus $\ln[t/(t - t_h)]$ during cooling process (i.e., $S = \Delta T/\Delta\ln[t/(t - t_h)]$).

The purpose of this study is to determine thermal conductivity using Eq. (6) of some soil types as affected by bulk density and moisture content using the cooling method. The results obtained using this method will be compared with the results obtained for the same soil types but using the heating method. Furthermore, thermal conductivity of other soil types will be evaluated using both methods and the results will be compared.

2. Materials and methods

The experiment was performed on four types of soils (sand, sandy loam, loam, and clay loam). Mechanical analysis of these soils is given in Table 1. Several tests were run for each soil type. These tests were based on different packing densities and different moisture contents of the samples.

2.1. Apparatus

The apparatus used in this study to measure thermal conductivity of soils is shown in Fig. 1. It is basically consisted of a rectangular box made of steel. An electrical wire ran through the center of the box lengthwise and was fastened at either end. The wire was attached to an 8.3 V dc power supply unit, which would heat the wire running through the box. A thermocouple was inserted from the side of the box to measure the wire temperature. This thermocouple was attached to a data logger, which would read soil temperature at the thermocouple terminals at specified time intervals.

2.2. Experimental procedure

Oven dried method was used to determine the moisture content of the sample. A small portion of soil was weighed and dried in an oven at 105°C for 24 h to determine the initial moisture content of the soil. The soil sample, which was used to determine thermal conductivity was weighed and then placed in the box. The sample was packed from the top to the desired wet bulk density by controlling the height of the soil sample. After that, the electrical wire was connected to the power supply unit. Temperature of the wire was recorded every 5 s for the first minute and then every 10 s till the end of the heating process (5 min). Then, the power supply unit is disconnected and cooling process would start immediately. The thermocouple continued to read the temperature of the wire after the battery was disconnected. Temperature of the wire was re-

Table 1
Particle size distribution and other soils information used

Type of soil	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Moisture content (%)
Sand	95.75	4.15	0.10	1.24	1.40
Sand	95.75	4.15	0.10	1.32	1.40
Sand	95.75	4.15	0.10	1.43	1.40
Sand	95.75	4.15	0.10	1.18	2.50
Sand	95.75	4.15	0.10	1.27	2.50
Sand	95.75	4.15	0.10	1.38	2.50
Sand	95.75	4.15	0.10	1.06	3.30
Sand	95.75	4.15	0.10	1.17	3.30
Sand	95.75	4.15	0.10	1.34	3.30
Sand loam	75.00	9.00	16.00	1.23	6.11
Sand loam	75.00	9.00	16.00	1.32	6.11
Sand loam	75.00	9.00	16.00	1.41	6.11
Sand loam	75.00	9.00	16.00	1.18	9.35
Sand loam	75.00	9.00	16.00	1.27	9.35
Sand loam	75.00	9.00	16.00	1.34	9.35
Loam	40.00	36.00	24.00	1.26	7.68
Loam	40.00	36.00	24.00	1.31	7.68
Loam	40.00	36.00	24.00	1.41	7.68
Loam	40.00	36.00	24.00	1.20	17.50
Loam	40.00	36.00	24.00	1.26	17.50
Loam	40.00	36.00	24.00	1.31	17.50
Clay loam	21.44	39.00	39.56	1.33	9.3
Clay loam	21.44	39.00	39.56	1.39	9.3
Clay loam	21.44	39.00	39.56	1.49	9.3
Clay loam	21.44	39.00	39.56	1.18	14.16
Clay loam	21.44	39.00	39.56	1.28	14.16
Clay loam	21.44	39.00	39.56	1.37	14.16
Clay loam	21.44	39.00	39.56	1.10	18.3
Clay loam	21.44	39.00	39.56	1.22	18.3
Clay loam	21.44	39.00	39.56	1.27	18.3

corded every 5 s for the first 30 s and then every 10 s till the end of the cooling process. Current was recorded for later use for the thermal conductivity calculations. The same procedure was repeated for three different soil densities at three different moisture contents for each soil type.

3. Results and discussion

Four parameters were measured in each experiment for all soil types: wire temperature, time at specified intervals, soil density, and moisture content.

The first step in determining the sample thermal conductivity is to calculate the slope of the temperature rise or fall versus the logarithm of the time curve. The characteristics of temperature fall versus the logarithm of time at different combinations of soil bulk densities and soil moisture contents are shown in Fig. 2. The characteristics of temperature rise versus the logarithm of time at different combinations of soil bulk densities and soil moisture contents are shown in Fig. 3. Slopes of these curves were determined and used in Eq. (6) to calculate the thermal conductivity.

The results can be viewed in graphical form in Fig. 4 for sandy soil, Fig. 5 for clay loam soil, Fig. 6 for sandy loam soil, and in Fig. 7 for loamy soil. As shown in all figures, bulk density and moisture content affected thermal conductivity of all soils. For the same moisture content, increasing the soil density increased its thermal conductivity. For the same soil density, soil thermal conductivity increased with increasing moisture content. This agreed with Ghauman and Lal [4], who found that thermal conductivity increased with increasing soil water content. In general, all figures show that sandy soil had higher thermal conductivity than for clay loamy soil at all water contents and bulk densities studied. The mineralogical constituents of the sandy soil have higher thermal conductivity than the corresponding clay minerals.

The maximum thermal conductivity (2.01 W m^{-1} K) was observed in sandy soil. Thermal conductivity values reported here lie well within the range 0.3–2.25 W m^{-1} K for sandy soil as given by Van Wijk [7], and

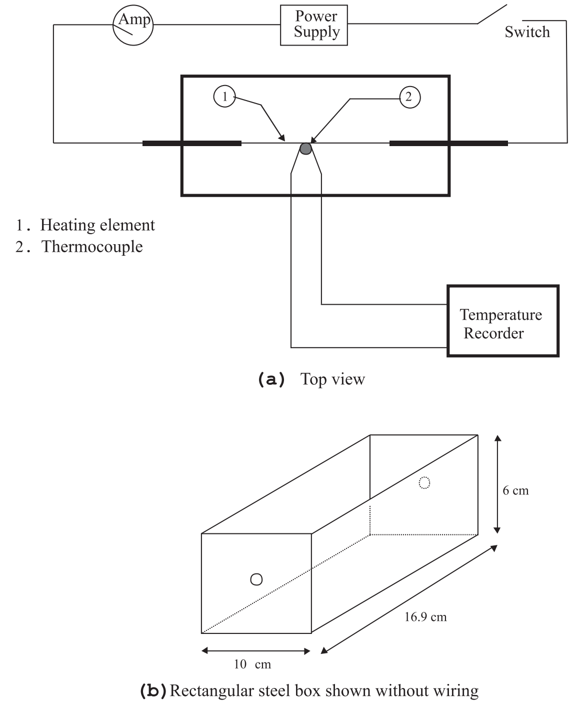

Fig. 1. Schematic diagram of the experimental apparatus.

within the range 0.15–0.79 W m^{-1} K for loam soil as given by Ghauman and Lal [4]. The values obtained for thermal conductivity are higher than the 0.59 W m^{-1} K obtained by Ghauman and Lal [4] for sandy loam soil at moisture content of 10%. The mineralogical differences and percentages of sand, silt, and clay in the sandy loam soil they examined and ours may account for this variation.

The statistical analysis software [6] was used to perform the statistical analysis on the data for sand and clay loam soils. BREG analysis was used to find the best model that expresses the soil's thermal conductivity as a function of its density and moisture content. Mixed multiple regression was performed on the variables obtained from BREG analysis. The final regression equations for both soils are as follow:

For the sandy soil (*heating method*):

$$K_{\text{sand-heating}} = 0.54 + 1.04D_{\text{sand}} - 1.86(D_{\text{sand}})(MC_{\text{sand}}) + 0.259(D_{\text{sand}})(MC_{\text{sand}})^2 + 0.754(D_{\text{sand}})^2(MC_{\text{sand}}) \quad (R^2 = 97.9\%).$$

For the clay loam soil:

$$K_{\text{clay-heating}} = -0.572 + 0.554D_{\text{clay}} + 0.00257(D_{\text{clay}})(MC_{\text{clay}})^2 + 0.0167(D_{\text{clay}})^2(MC_{\text{clay}}) \quad (R^2 = 88.2\%),$$

where D_{sand} and D_{clay} are the density of sandy soil and clay loam soil, MC_{sand} and MC_{clay} the moisture content of sandy soil and clay loam soil, $K_{\text{sand-heating}}$ and $K_{\text{clay-heating}}$ are the thermal conductivity of sandy soil and clay loam soil.

Statistical analysis was performed on the data for each soil type using the statistical analysis software [6]. The analysis was performed at a 10% level of significance, where the null hypothesis was the conductivity values at certain moisture content for each soil type have

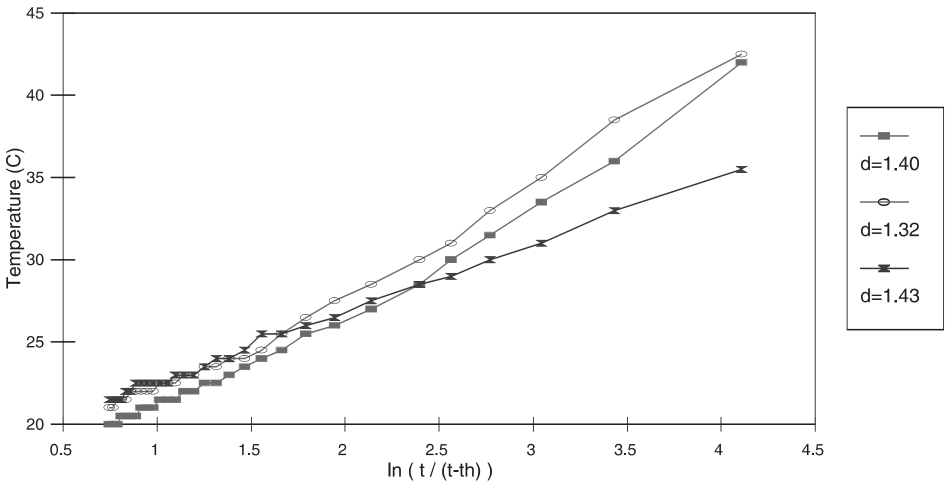

Fig. 2. Wire temperature as a function of $\ln(t/(t-t_h))$ during cooling for sandy soil at moisture content of 1.4% and different soil densities (g cm^{-3}).

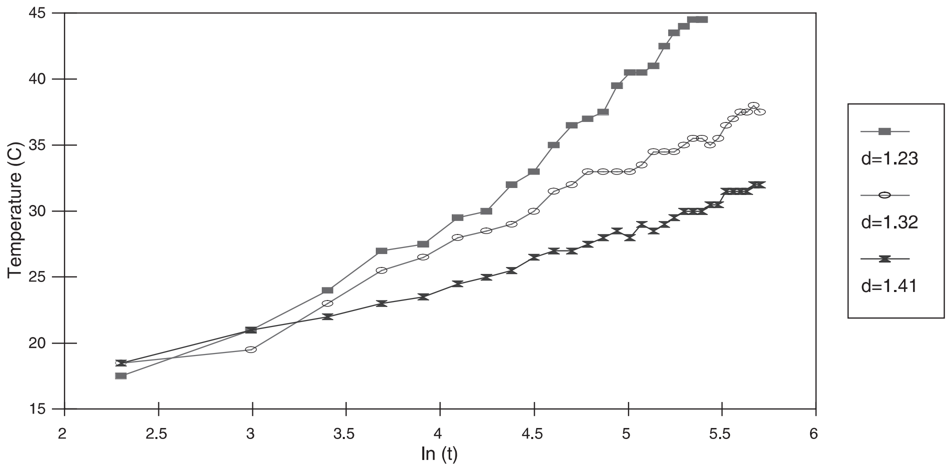

Fig. 3. Wire temperature as a function of $\ln(t)$ during heating for sandy loam soil at moisture content of 1.4% and different soil densities (g cm^{-3}).

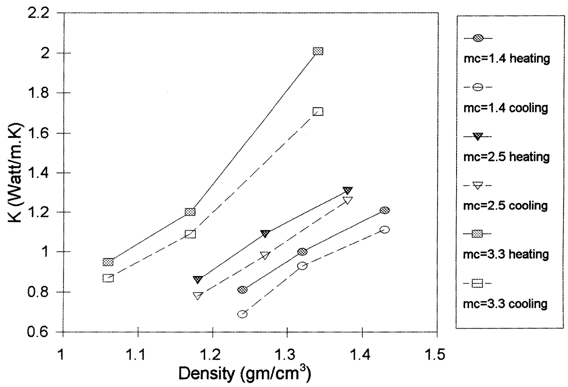

Fig. 4. Thermal conductivity as a function of soil density for sandy soil at three different moisture contents (1.4%, 2.5% and 3.3%).

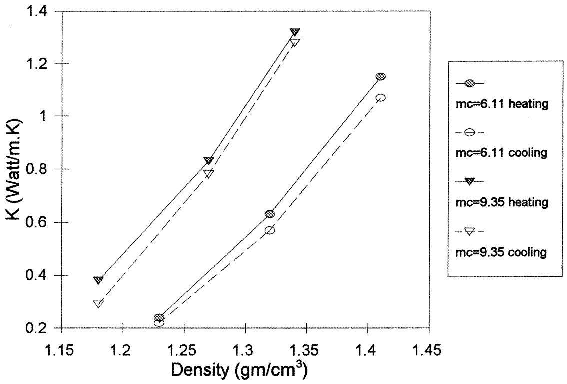

Fig. 6. Thermal conductivity as a function of soil density for sandy loam soil at two moisture contents (6.11% and 9.35%).

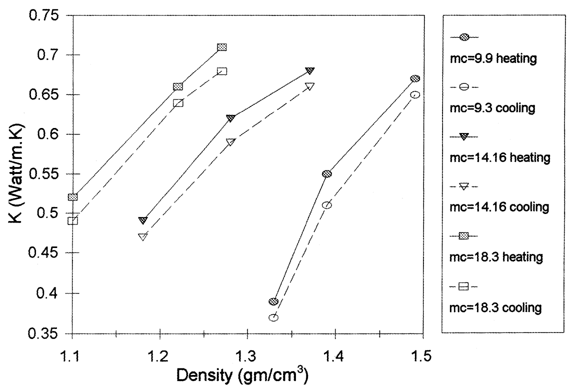

Fig. 5. Thermal conductivity as a function of soil density for clay loamy soil at three different moisture contents (9.3%, 14 2% and 18.3%).

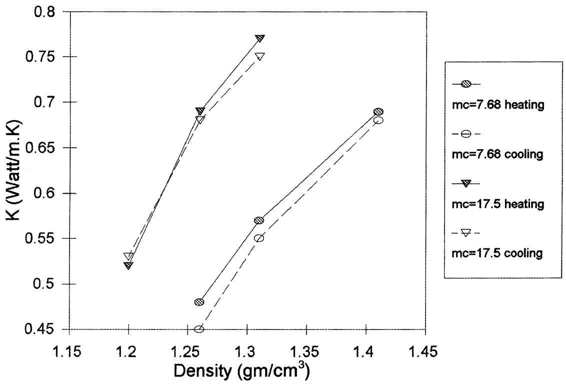

Fig. 7. Thermal conductivity as a function of soil density for loamy soil at two moisture contents (7.68% and 17.5%).

Table 2
Statistical comparison of thermal conductivity values obtained by heating and cooling methods for the four soils[a]

	Sand			Clay loam			Sandy loam		Loam	
	$MC = 1.40$	$MC = 2.50$	$MC = 3.30$	$MC = 9.30$	$MC = 14.16$	$MC = 18.30$	$MC = 6.11$	$MC = 9.35$	$MC = 7.68$	$MC = 17.50$
K-heating	1.00(a)	1.08(a)	1.38(a)	0.53(a)	0.59(a)	0.63(a)	0.67(a)	0.84(a)	0.58(a)	0.66(a)
K-cooling	0.96(a)	1.00(a)	1.25(a)	0.51(a)	0.57(a)	0.60(a)	0.63(a)	0.79(a)	0.56(a)	0.65(a)

[a] Means represent four measurements in each K determination method. Means in columns, within a K determination method, followed by the same letter were not significantly different at a 10% level.

the same mean. Table 2 shows comparisons of the average conductivity values obtained using heating and cooling methods at different moisture contents for sand, sandy loam, loam, and clay loam soils. As shown in Table 2, there is no significant difference between the average values obtained by heating and by cooling for all soil types studied at all moisture contents. The thermal conductivity determined using the cooling data was smaller than that determined using the heating data. One possible reason is the complicating factors arising from water movement in response to temperature gradients caused by the heating. Low power inputs were used since lower power inputs are preferable to minimize the effects of heating on soil water movement and hence thermal conductivity.

4. Conclusions

The results of the cooling process show that thermal conductivity varies with bulk density, moisture content, and soil texture. In general, for the four types of soil used in this study, an increase in moisture content at a given density increased thermal conductivity. At a given moisture content, increasing soil density increased thermal conductivity. This is in total agreement with the results obtained using the heating process of the electrical wire. In general, the heating data yielded thermal conductivities that were slightly higher than those derived from the cooling data. A clay loam soil had lower thermal conductivity than a sandy soil. These results show that a simple and low cost probe for measuring soil thermal conductivity could be designed. It could be used to measure soil thermal conductivity on the go in the field.

References

[1] K.L. Bristow, G.J. Kluitenberg, R. Horton, Measurement of soil thermal properties with a dual-probe heat-pulse technique, Soil Sci. Soc. Am. J. 58 (1994a) 1288–1294.

[2] G.S. Campbell, C. Callissendrorff, J.H. Williams, Probe for measuring soil specific heat using a heat pulse method, Soil Sci. Soc. Am. J. 55 (1991) 291–293.

[3] D.A. De Vries, A nonstationary method for determining thermal conductivity of soil in situ, Soil Sci. 73 (1952) 83–89.

[4] B.S. Ghauman, R. Lal, Thermal conductivity, thermal diffusivity, and thermal capacity of some Nigerian soils, Soil Sci. 139 (1985) 74–80.

[5] R.D. Jackson, S.A. Taylor, Heat transfer, Am. Soc. Agron., in: C.A. Black (Ed.), Methods of Soil Analysis, Part 1, Agronomy, Madison, Wisconsin, 9, 1965, pp. 349356.

[6] MINITAB, Minitab Release 10.2. Minitab Inc. State College, PA. (1994).

[7] W.R. VanWijk, Physics of Plant Environment, North-Holland, Amsterdam, 1963.