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Effective Thermal Conductivity Measurement of Soil

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ABSTRACT

This paper presents experimental results of the effective thermal conductivity measurements of soils. The heat flow method was used in measuring thermal conductivities. Various types of local soil samples were used. They were red-soil (loam), kurnub sandstone, and limestone. The heat flow method allows good configuration of sample preparation in the laboratory. Briefly, the soil sample is placed in a container having a square shape with the dimensions of 30 cm on the side and a thickness of 1. 5 cm. The sample is then placed between two hot and cold plates. The apparatus is equipped with computer data acquisition system and set point control of hot plate temperature. Since it is operated using the heat flow method, this kind of system allows testing of any type of granular, construction, or insulation materials of even low thermal conductivities. Results show that that thermal conductivities of red soil, kurnub sandstone, and limestone were 0. 178, 0. 251, and 0. 223 W/m·K, respectively. Thermal conductivities of red soil-kurnub sandstone mixtures were also reported. It was found that soils containing higher percentages of kurnub sandstone had higher thermal conductivity values. The relationship was a linear one. Effect of moisture content on thermal conductivity was also studied. In general, the thermal conductivity was higher as the result of increasing soil's moisture content.

Keywords: effective thermal conductivity, soil

INTRODUCTION

Soil thermal conductivity is one of the most important thermophysical properties, especially for agricultural, metrological and engineering applications [1, 2]. It is the property of the material that expresses the heat flux that controls heat flow through it by conduction when a certain temperature gradient exists. Soils are porous solid materials affected by their moisture content. Also, the thermal conductivity of water is much higher than that of air. Therefore, soils with higher moisture contents have higher values of effective thermal conductivities.

There are several methods used in determining thermal conductivity of solid materials. For example, Garcia and co-workers have presented experimental comparison of two methods for thermal conductivity measurements of geothermal cements [3-5]. They compared two methods of measurements, which were the Jaeger and line source methods. It was found that the heat line source method has lower uncertainty values than those obtained using the Jaeger method. Ochsneret al presented the heat-pulse method for evaluating effective thermal conductivities [6, 7]. Tavmanpresented effective thermal conductivity of granular materials as a function of moisture content, which was obtained using line heat source technique[8, 9]. They have found that there was a linear relationship between moisture content and thermal conductivity. Other methods also can be used such as hot wire technique [10]. Abu-Hamdeh et al. presented results of thermal conductivity of soils using hot wire heating and cooling methods[11]. It was found that heating method yielded thermal conductivity data that were slightly higher than those obtained from cooling method. Also, Abu-Hamdehused single-and dual-probe methods in other studies [12-15]. There was slight difference in thermal conductivity values for various types of soils when single-probe method was used and compared with dual-probe method. Other studies were reported and showed that measurements of thermal conductivity using the two methods yield similar values [16, 17]. It was concluded that when determining thermal conductivity from the single probe data, it is best to use nonlinear curve fitting and to include a correction term in the model to account for the presence of the probe. In situ measurement of ground thermal conductivity was presented by Witte et al [18]. Another method of determining thermal properties was reported by Fontana et al [19]. Other studies have presented relationship between thermal conductivity and water content of soils using numerical modeling [20]; also, other studies were conducted for different soils in different regions [21-29].

The main objective of this work is to determine effective thermal conductivities of some mixtures of Jordanian soils at various moisture contents to optimize soil mixing for planting and thus reduce transient temperature effect on plant roots. The samples were obtained from local surroundings. The selected samples were similar to those commonly used in plantation. The heat flow method was used for such measurements.

MATERIALS AND METHODS

A schematic diagram of the thermal conductivity measurement unit used in this study is presented in Fig. 1. It is designed for measuring effective thermal conductivities of building and insulating solid materials. It is operated based on heat flow method. Briefly, the sample of soil is placed in a container having a square shape with the dimensions of 30 cm on the side and a thickness of 1. 5 cm. In order to avoid thermal contact resistance two silicon rubber mats were used as covers to the sample. The sample is then placed between two hot and cold plates. The top hot plate was electrically heated, while the lower cold plate was cooled by running tab water through the heat exchange surface of the cold pate. The temperature difference between hot and cold plate can be set at a constant value. The system is well insulated and the flow of heat is considered as one-dimensional steady-state conduction. Throughout all of our experiments reported in this study, it was kept at 15ºC temperature difference. The apparatus is equipped with computer and data acquisition system with set point control of hot plate temperature. The cold plate is kept cooled by running tab water through it. Since it is operated using the heat flow method, this kind of system allows testing of any type of granular, building, or insulating materials with even low thermal conductivity value to be measured.

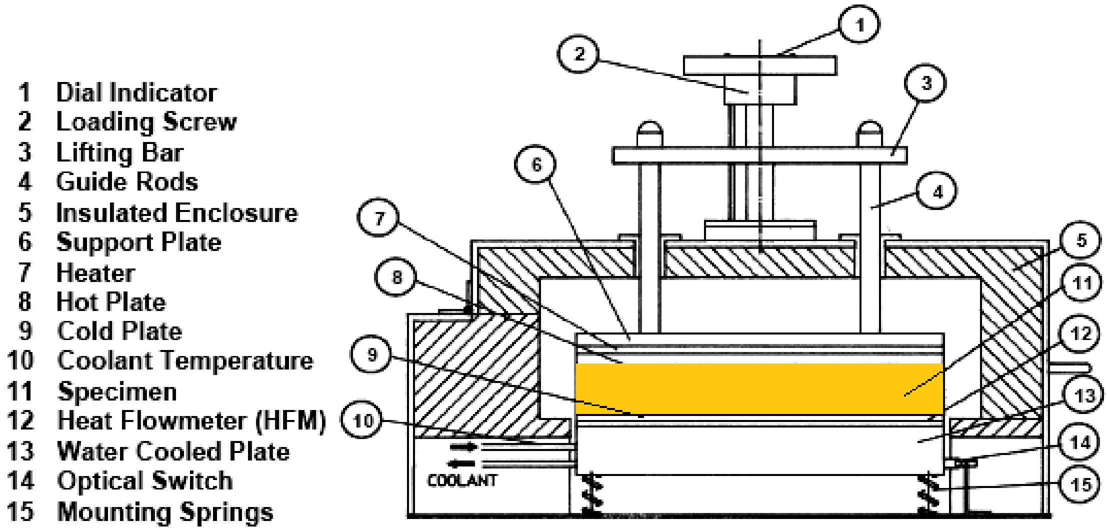

Figure 1. Schematic diagram of the experimental setup

Various types of soils were used in this study. The samples used were red-soil (loam), kurnub sandstone, and limestone. They were obtained locally. First, they were dried in an oven under vacuum at a temperature of 60 ºC. Selected samples were sieved and the particle or grain size distribution was obtained. Fig. 2 presents grain size distribution of two types of soils; they were red soil and kurnub sandstone. Red soil has a smaller average size distribution than kurnub sandstone. Based on mass basis, more than 50% of the particles in red soil have diameters of 0. 5 mm and above. Whereas, more than 50% of the particles of kurnub sandstone have diameters of about 3 mm and above. Various mixtures of red soil and kurnub sandstone were prepared by thoroughly mixing large samples. Similarly, soils at variable moisture contents were prepared in order to study the effect of moisture content on thermal conductivity of soil.

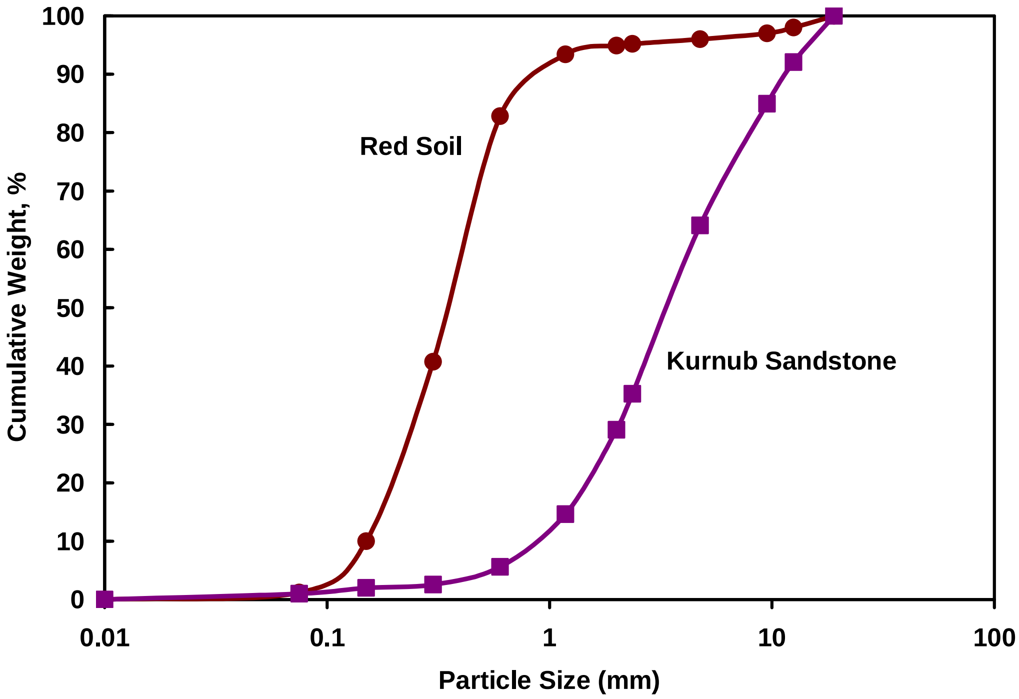

Figure 2. Grain size distributions of red soil and kurnub sandstone

Simply, the principle that our experimental setup uses is based on Fourier's Law of conduction which states that: for one-dimensional steady-state conduction heat transfer can be written as the following relationship [30]:

$$q_x = -kA\frac{dT}{dx} = kA\frac{\Delta T}{\Delta x} \tag{1}$$

where, q_x, is the x-dimension heat transfer, k is the thermal conductivity of the solid material to be obtained, A is the area perpendicular to the flow of heat, and dT/dx is the temperature gradient. Therefore, if we use a material with a known area A, a known thickness Δx, and a fixed temperature difference, ΔT, then the value of k can be determined if we can measure q_x. Therefore, measuring the one-dimensional heat transfer rate becomes essential. The described apparatus gives us the capability to measure heat transfer rate since the principle of the apparatus is based on the heat flow method. Heat is provided from the top hot plate to the lower colder plate. All the values are recoded by a computer-data acquisition setup. And thus, k can be obtained by rearranging Eq. (1) as follows:

$$k = \frac{q_x}{A}\frac{\Delta x}{\Delta T} \tag{2}$$

RESULTS AND DISCUSSION

Effective thermal conductivities of different types of soils dried as received were obtained, individually. They are presented in Figure 3. The figure shows that kurnub sandstone has the highest value ofthermal conductivity of 0. 251 W/m·K, followed by limestone with a value of 0. 223 W/m·K, and finally, red soil with 0. 178 W/m·K.

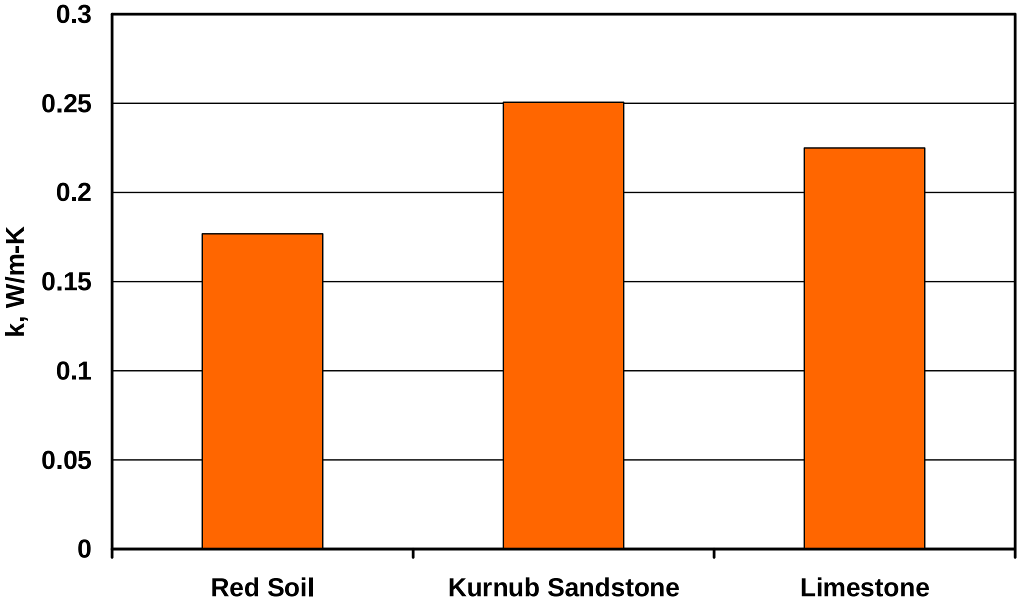

Figure 3. Effective thermal conductivities of red soil, kurnub sandstone, and limestone

Mixtures of soils with various ratios were prepared in order to determine the effect of mixing on the obtained values of the thermal conductivities. For example, dry red soil was mixed with dry kurnub sandstone at different percentages. Figure 4 shows the results of such mixing. The reason for such mixing is that in Jordan most farmers mix red soil with kurnub sandstone for enriching the soil with higher amounts of water due to the high permeability of sandstone, which allows higher amounts of water to reach the roots of the plants. As shown by the figure where “0% sandstone” means only dry red soil is present. Whereas, “100% sandstone” indicates dry sandstone is present, solely. The figure shows that thermal conductivity increases with presence of sandstone in the red soil-sandstone mixture according to a linear relationship:

$$k_{mixture} = (1-x)k_{soil} + xk_{sandstone} \tag{3}$$

where, $k_{mixture}$ is the thermal conductivity of the red soil-sandstone mixture, k_{soil} is the thermal conductivity of the red soil, $k_{sandstone}$ is the thermal conductivity of the kurnub sandstone, and *x* is the mass fraction of sandstone in the mixture. Equation (1) is plotted a straight line in Figure 4.

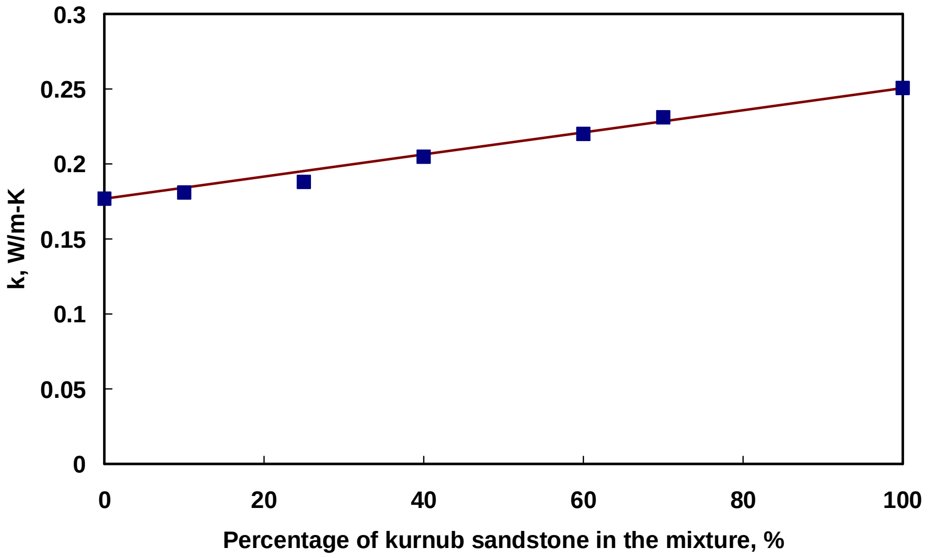

Figure 4. Effective thermal conductivity of dry red soil-sandstone mixtures versus percentage of sandstone in the mixture

It is important to point out that the results obtained have to reach steady-state conditions. This was accomplished after about 2 hours from the beginning of the experiment. Figure 5 shows variations of measured thermal conductivities of various soils as a function of time. The figure presents results of red soil data at various moisture content percentages reaching up to 30%. Similar trends were obtained for all other experimental data points. The final results obtained from these data are presented in Figure 6.

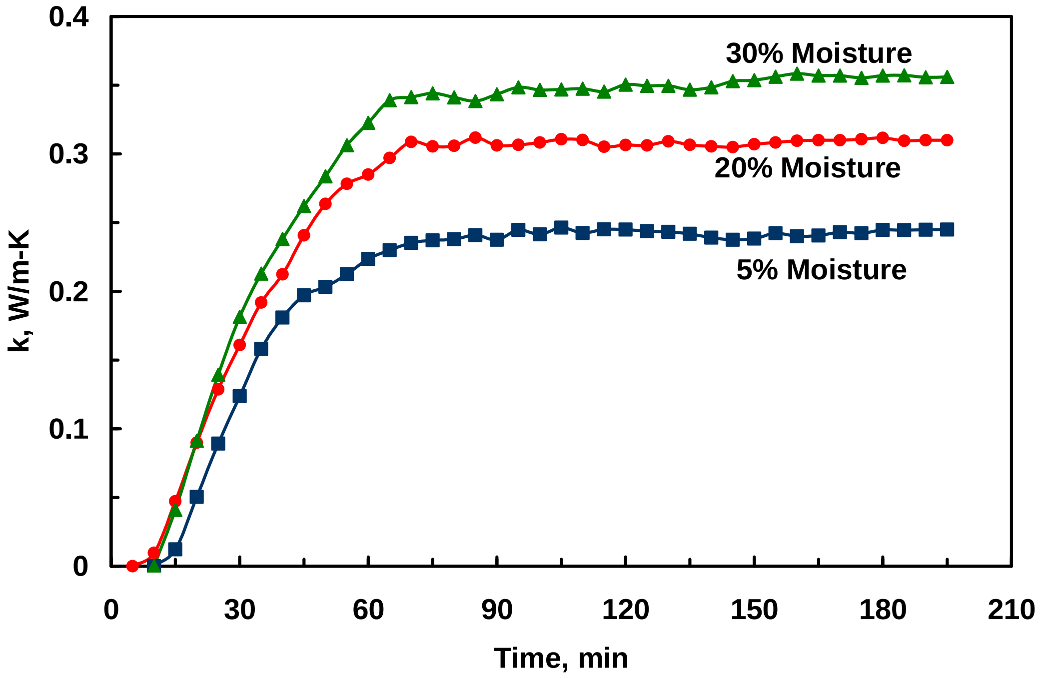

Figure 5. Effective thermal conductivity of red soil versus time at various moisture contents

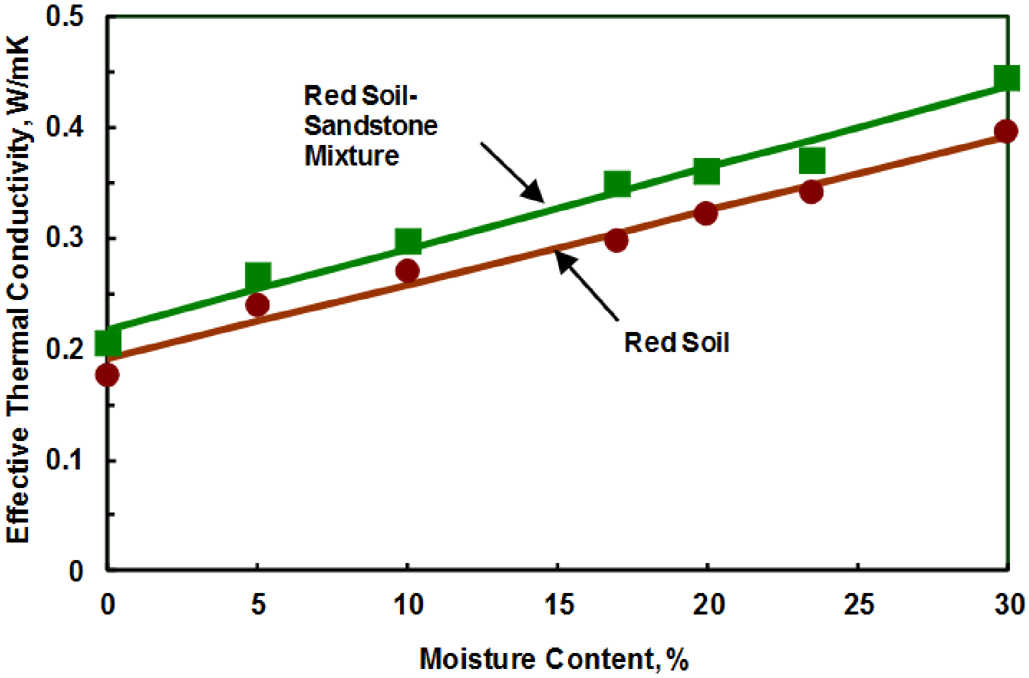

Figure 6. Linear relationship between effective thermal conductivity of red soil and mixture of red soil with sandstone versus moisture content

Figure6 shows the effect of variation of moisture content on effective thermal conductivity of soils. The data are presented to show the effect of moisture on soil in one set of experimental results which is labeled as “Red Soil” on the figure. Similar results were obtained when red soil was replaced with a red soil and kurnub sandstone mixture. The mixture was prepared from mixing 60% red soil with 40% sandstone on mass basis. The data are labeled as “Red Soil-Sandstone Mixture” on Figure 6. Clearly, the results show that effective thermal conductivity increases with moisture content. Moisture content was limited to 30% because higher moisture contents cause the sample to become very muddy and it becomes more like a fluid than a solid, and our experimental setup is designed to test solid materials only.

CONCLUSION

It can be concluded that the heat flow technique was used to experimentally determine effective thermal conductivities of different types of locally available Jordanian soils at variable moisture contents. They were red-soil, kurnub sandstone, and limestone. The heat flow method is considered to have good configuration of sample and ease of preparation in the lab. The results were very consistent with those available in literature. For example, addition of moisture increases thermal conductivity of soils in a linear relationship. Results showed that that thermal conductivities of red soil, kurnub sandstone, and limestone were in the order of 0. 178, 0. 251, and 0. 223 W/m·K, respectively. Thermal conductivities of red soil-kurnub sandstone mixtures were also studied. It was found that soils containing higher percentages of kurnub sandstone had higher thermal conductivity values. The relationship was linear. Effect of moisture content on thermal conductivity was also reported. In general, thermal conductivity increased with increasing soil’s moisture content. The study was effective in determining effect of mixing soils together. It was found that a linear relationship can be obtained also. Future studies need to determine the effect of surrounding temperature on thermal conductivity of soil.

References

[1] O. Johansen, *Thermal Conductivity of Soils*, Ph. D. thesis. Trondheim, Norway, 1975.

[2] T. E. Ochsner, R. Horton, T. Ren. A New Perspective on Soil Thermal Properties. *Soil Science Society of America Journal*, 2001, vol. 65(6)pp. 1641-1647.

[3] Garcia-Gutierrez A, Espinosa-Paredes G. Thermal conductivity measurement of geothermal cementing systems: an experimental comparison between the line source and Jaeger methods. *Energy Conversion and Management*, 2004, vol. 45 pp. 755-764.

[4] G. Espinosa-Paredes, A. Garcia, E. Santoyo, E. Contreras, J. Morales. Thermal property measurement of Mexican geothermal cementing systems using an

experimental technique based on the Jaeger method. *Applied Thermal Engineering*, 2002, vol. 22, pp. 279-294

[5] E. Santoyo, A. García, J. Morales, E. Contreras, G. Espinosa-Paredes. Effective thermal conductivity of Mexican geothermal cementing systems in the temperature range from 28°C to 200°C. *Applied Thermal Engineering*, 2001, Vol. 21, pp. 1799-1812

[6] T. E. Ochsner, R. Horton, T. Ren. Simultaneous Water Content, Air-Filled Porosity, and Bulk Density Measurements with Thermo-Time Domain Reflectometry. *Soil Science Society of America Journal*, 2001, vol. 65(6), pp. 1618-1622

[7] T. Ren, T. E. Ochsner, R. Horton, Z. Ju. Heat-Pulse Method for Soil Water Content Measurement. *Soil Science Society of America Journal*, 2003, vol. 67 (6)pp. 1631-1634

[8] S. Tavman, I. Tavman. Measurement of effective thermal conductivity of wheat as a function of moisture content. *International Communications in Heat and Mass Transfer*, 1998, Vol. 25, pp. 733-741

[9] I. H. Tavman. Effective thermal conductivity of granular porous materials. *International Communications in Heat and Mass Transfer*, 1996, Vol. 23, pp. 169-176

[10] M. J. Assael, M. Dix, K. Gialou, L. Vozar, W. A. Wakeham. Application of the Transient Hot-Wire Technique to the Measurement of the Thermal Conductivity of Solids. *International Journal of Thermophysics*, 2002, Vol. 23, pp. 615-633

[11] N. Abu-Hamdeh, A. Khdair, R. Reeder. A comparison of two methods used to evaluate thermal conductivity for some soils. *International Journal of Heat and Mass Transfer*, 2001, vol. 44, pp. 1073-1078

[12] N. Abu-Hamdeh. Thermal properties of soils as affected by density and water content. *Biosystems Engineering*, 2003, 86 (1), pp. 97-102

[13] N. Abu-Hamdeh. Effect of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils. *Soil and Tillage Research*, 2000, Vol. 56 (3), pp. 145-151

[14] N. Abu-Hamdeh. SW-Soil and water: measurement of the thermal conductivity of sandy loam and clay loam soils using single and dual probes. *Journal of Agricultural Engineering Research*, 2001, Vol. 80, pp. 209-216

[15] N. Abu-Hamdeh, R. Reeder. Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. *Soil Science Society of America Journal*, 2000, Vol. 64 (4), pp. 1285-1290

[16] K. Bristow, G. Kluitenberg, R. Horton. Measurement of Soil Thermal Properties with a Dual-Probe Heat-Pulse Technique, *Soil Science Society of America Journal*, 1994; vol. 58, pp. 1288-1294

[17] K. Bristow, R. White, G. Kluitenberg. Comparison of single and dual probes for measuring soil thermal properties with transient heating, *Australian Journal of Soil Research*, 1994, vol. 32(3), pp. 447–464

[18] H. Witte, G. van Gelder, J. Spitler. In Situ Measurement of Ground Thermal Conductivity: A Dutch Perspective. *ASHRAE Transactions*2002, vol. 108(1), Paper 4521, pp. 263-272

[19] A. Fontana, B. Wacker, C. Campbell, G. Campbell. Simultaneous thermal conductivity, thermal resistivity, and thermal diffusivity measurement of selected foods and soils. *American Society of Agricultural Engineers Meeting*, Paper 01-6101, Sacramento, California, USA, 2001

[20] P. Cosenza, R. Guérin andA. Tabbagh. Relationship between thermal conductivity and water content of soils using numerical modeling, *European Journal of Soil Science*, 2003, Vol. 54, Issue 3, pp. 581–588

[21] A. Bouazza, R. Singh, R. Rowe, F. Gassner. Heat and moisture migration in a geomembrane–GCL composite liner subjected to high temperatures and low vertical stresses. *Geotextiles and Geomembranes*, 2014, vol. 8, pp. 555-563

[22] D. Barry-Macaulay, A. Bouazza, R. Singh, B. Wang, P. Ranjith. Thermal conductivity of soils and rocks from the Melbourne (Australia) region. *Engineering Geology*, 2013, vol. 6, pp. 131-138

[23] R. Singh, A. Bouazza. Thermal conductivity of geosynthetics. *Geotextiles and Geomembranes*, 2013, VOL. 6, PP. 1-8

[24] H. Kim, H. Kwon, J. Lee, N. Cho, H. Kim. Thermal Conductivity Measurement of Saturated Clayey Mixtures using Oedometer Consolidation and Constant Rate of Strain Consolidation Tests, *The Journal of Engineering Geology*, 2012, vol. 3, pp. 275-281

[25] D. Barry-Macaulay, A. Bouazza, R. Singh. Study of Thermal Properties of a Basaltic Clay. *Geo-Frontiers*, 2012, Paper 2011480-487.

[26] M. de Moel, P. Bach, A. Bouazza, R. Singh, J. Sun. Technological advances and applications of geothermal energy pile foundations and their feasibility in Australia. *Renewable and Sustainable Energy Reviews*, 2010, vol. 7, pp. 2683-2696

[27] P. Ayub Khan, M. Madhav, E. Saibaba-Reddy. Consolidation of thick clay layer by radial flow-non-linear theory. *Geomechanics and Engineering*, 2010, vol. 2, pp. 157-160

[28] R. Hotz, L. Ge. Investigation of the thermal conductivity of compacted silts and its correlation to the elastic modulus, *Journal of Materials in Civil Engineering*, 2009, pp. 408-412.

[29] H. Abuel-Naga, D. Bergado, A. Bouazza, M. Pender. Thermal conductivity of soft Bangkok clay from laboratory and field measurements. *Engineering Geology*, 2009, vol. 2. pp. 211-219

[30] F. Incropera, D. DeWitt, T. Bergman, A. Lavine. *Foundations of Heat Transfer*, 2012, 6th Edition, John Wiley & Sons, N. Y., USA.