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DETERMINATION OF THERMAL CONDUCTIVITIES OF SOME TOPSOILS USING BLOCK METHOD

[1*] Y. S. Onifade, [2] O. D. Akinyemi and [3]R. Bello

[1]*Department of Physics, Federal University of Petroleum Resources, Effurun, Nigeria*
[2]*Department of Physics, Federal University of Agriculture, Abeokuta, Nigeria*
[3]*Department of Physics, University of Port Harcourt, Port Harcourt, Nigeria*
*(*onifade.yemi@fupre.edu.ng)*

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ABSTRACT

This study focuses on the determination of In situ measurement of the top soil layer, despite non-homogeneity of natural soils caused by changes in their water content, texture and structure. Thermal Conductivities of clay, loam and sand soils were determined using improved Block method with and without the use of Thermal Interface Material (TIM). KD2 Thermal Properties Analyzer was used to take instantaneous measurement of thermal conductivities with and without the use of TIM for validation. The results show increase with the application of TIM which follows the same trend with KD2 results .Thermal conductivity increases from 0.68 W/ mK to 0.85W/mK , for clay, 0.18WmK to 0.34WmK for loam and 0.34W/mK to 0.39W/mK for sand with Block method while 0.66W/mk to 0.84W/mK for clay, 0.17W/mK to 0.30W/mK for loam and 0.28 WmK to 0.33W/mK for KD2 analyzer.

Key words: Thermal Conductivity, Block method, Topsoil. Thermal Interface Material, Thermal gradient.

INTRODUCTION

The thermal properties of interest for any material include thermal conductivity, thermal diffusivity, and volumetric heat capacity. The thermal conductivity is an index related to the rate of heat flow and the thermal diffusivity corresponds to the rate of temperature change for a particular material when a temperature gradient exists, while the volumetric heat capacity indicates the thermal capacity of that material.

For better understanding of transport mechanism in soils, rocks and other engineering materials, the effective thermal conductivity of porous media has been studied for well over one hundred years in both theory and experiment (Muskat and Wyckoff, 1937). Recently, it has gained more attention due to its new applications in functional material design, textile and food engineering and even human medical technologies (Gluldyal and Triphati, 1973).

In experiments, hot-wire and hot-probe are the most popular techniques for local thermal conductivity measurement for soft matter, which are based on a linear heat source and an axis-symmetric measurement system (Ingham and Pop, 2005). They have been used for measuring the thermal conductivities of soils, foods and even liquids (Singh *et. al.,* 1990). In high porosity solid structure cases, however, the parallel plate and hot plate have been more frequently used and recently, a comparative method to measure the thermal conductivity in highly non-homogeneous cases was developed (Ingham and Pop, 2005).

The thermal properties of soils are of great importance to agriculture and engineering, especially in relation to temperature and heat flux in the root and rock zones. It is also important in studying energy, water balance and mass exchange processes occurring across porous media surfaces. The connection between thermal conductivities and moisture content of a soil obtained in the laboratory has also been used to determine these properties in the field (Akinyemi and Mendes, 2007). The thermal parameters depend mainly on the soil type and constituents, soil texture, porosity and moisture content. The heat capacity is a material property, which expresses the fact that for changing temperature of a certain volume of material, energy must flow in or out. The heat capacity is usually linked to the density of the material. When dynamic processes are involved, the change of temperature versus time, at known boundary conditions is determined by both thermal conductivity and heat capacity. It is a known fact that the heat form of transformation and transfer of the Earth's inner energy determines such fundamental parameter as the temperature of depths, which in turn influences the physical properties of depth, their phase conditions, metamorphic processes and other fundamental properties of the Earth (Carslaw and Jaeger, 1959).

The study of the thermal conductivities of soils has been conducted for several decades with a great variety of aims. For the rocks for example, when one wished to determine geothermal heat flux, it was necessary to measure the conductivity of a drilling core or for hydrocarbon studies it was necessary to estimate the oil content of the porous rocks (Carslaw and Jaeger, 1959).

It is hard to say something general about the soil thermal conductivities at a various locations because of variation of altitude and flux density which affect temperature. Apart from the basic soil composition, which is constant at each location, soil thermal conductivities are strongly influenced by the soil volumetric water content, volume fraction of solid and volume fraction of air. Air is a poor thermal conductor and reduces the effectiveness of the solid and liquid phases to conduct heat. While the solid phase has the highest thermal conductivity, it is the variability of soil moisture that largely determines thermal conductivity. As such soil moisture properties and soil thermal conductivities are very closely linked and are often measured and reported together. Temperature variations are most extreme at the surface of the soil and these variations are transferred to sub surface layers but at reduced rates as depth increases (Chu-Kuan Lin *et al.,* 2008)

Knowledge of the thermal conductivities of the topsoil layer is of great importance in studying energy and mass exchange processes occurring across the soil surface. However their determination In situ is extremely difficult, especially for the top soil layer, due to the non-homogeneity of natural soils caused by changes in their water content, texture and structure (Van Wijk and Belghith, 1965).

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In many problems one needs to know the thermal conductivities of the topmost layers of the soil. It is a well-known fact that the structure (porosity, air and moisture regime, density) of the upper layers is completely different from that of the deeper layers, and also thermal conductivities differ between upper and deeper layer (Akinyemi *et al.*, 2011 a & b)

Consequently, problems concerning the thermal balance of the surface layer of the soil must necessarily be based on the thermal conductivities of the soil surface layer. Knowing therefore the various earth thermal properties is very important in environmental geophysics and engineering.

Soil water content and soil compaction are two factors influencing a soil's thermal conductivity that can be managed externally (Abu-Hamdeh, 2003). Water content plays a major role in a soil's thermal conductivity and the most difficult to manage. Managing these two factors properly will greatly help in determining soil thermal conductivity (Aggarwal *et al.*, 2009; Maity and Aggarwal, 2012). Any practice or process, which tends to cause soil compaction will increase bulk density and decrease porosity of a soil. This in turn will have a significant effect on thermal conductivity. Estimation of heat flux from the soil temperature data can provide an understanding of the gain or loss of heat by the soil from the atmosphere (Chacko and Renuka, 2002).

MATERIALS AND METHOD

Study Area

Abeokuta was chosen as our study area (Fig. 3b). This was influenced by the fact that this region of the country is very much affected by geological exploration activities due to well-logging and bore-hole construction (Fasunwon *et. al.*, 2008) and Akinyemi *et al.,* 2012). Nigeria (Fig. 3a) lies between latitudes 5° and 14°N and longitudes 3° and 14°E and crystalline basement rocks of Precambrian age underlie about 50 % of the country (Muotoh *et al.,* 1988).

Block Method Theory

The basic equation governing heat flow in solids is Fourier equation

$$H = -\lambda \frac{\partial \theta}{\partial z} \qquad (1)$$

H is the quantity of heat flowing across a unit area of a virtual plane in the sample per unit time and called heat flux density while λ (W/mK) is the thermal conductivity. The factor $\partial\theta/\partial z$ is the temperature gradient in the direction normal to the virtual plane. The variation of the temperature in the rocks and soils depend on the ratio $a = \lambda/ C$ which is called thermal diffusivity and C (J/m^3 °C) is the Volumetric heat capacity

The temperature near the center of the contact plane is calculated from the theory of two bodies which are suddenly brought into contact along the plane z = 0 at the instant t = 0 (Caslaw and Jaeger, 1959). At the instant t = 0, the temperature changes according to the equation:

$$\frac{\delta\theta_i(z,t)}{\delta t} = a_i \frac{\delta^2\theta_i(z,t)}{\delta z^2} \qquad (2)$$

With i = 1 for Block apparatus, and i = 2 for sample used. Thermal diffusivity a_i (m^2/sec) = $\lambda/ C = \lambda/ \rho c$, with λ (W/mK) is the thermal conductivity, c (J/ kg °C) is the heat capacity per unit mass, ρ (kg/m^3) is the density, and C (J/m^3 °C) is the Volumetric heat capacity. Using the Laplace Transform of θ_1 (z, t), the general solution is given as (Van Wijk, 1966):

$$L\{ \theta_i (z,t)\} = A \exp\left(-z \sqrt{\frac{p}{a_i}}\right) + B_i \exp\left(+ z\sqrt{\frac{p}{a_i}}\right) + S_i (z,p) \qquad (3a)$$

Where A_i and B_i are a function of p only, and S_i is a particular solution :

$$S_i = \frac{T_{1\,in} + E_i z}{p} \qquad (3b)$$

The experimental description made by Van Wijk (1967) and elaborated by Stigter (1968) is based on solving the Fourier equation for two finite bodies having different initial temperatures and brought at time t = 0 in contact and at plane z = 0. According to Van Wijk (1967) the solution for the temperature of the block's contact plane is given as:

$$T_1(0,t) = \frac{T_{1in}\sqrt{\lambda_1 C_1} + T_{2in}\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}} + \frac{2}{\pi}\frac{\lambda_1 E_1 + \lambda_2 E_2}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}}\sqrt{t} \qquad (4)$$

where T_{1in} is initial surface temperature of the block.

Equation (4) for uniform temperature of the porous media reduces to (provided $\lambda_1 = \lambda_2$)

$$T_1(0,t) = \frac{T_{1in}\sqrt{\lambda_1 C_1} + T_{2in}\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}} \qquad (5)$$

Equation (5) can be expanded as follows.

$$T_1(0,t)\left(\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}\right) = T_{1\,in}\sqrt{\lambda_1 C_1} + T_{2\,in}\sqrt{\lambda_2 C_2} \qquad (6)$$

where $T_1(0,t)$ is Temperature of the block at t = 0, $T_{2\,in}$ is the surface temperature of the porous medium at t = 0, λ_1 is the thermal conductivity of the block material (Perspex), C_1 is the volumetric heat capacity of the block material (Perspex), λ_2 is the thermal conductivity of the porous medium and C_2 is the volumetric heat capacity of the porous medium.

Thus $T_1(0,t)(1 + \alpha) = T_{1\,in} + \alpha\, T_{2\,in}$ (7)

$$\text{where } \alpha = \frac{\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1}} \qquad (8)$$

From equation (4), a plot of $T_1(0,t)$ vs $\sqrt{t}$ will yield a straight line graph with intersect $T_1(0,0)$ at t = 0. Using temperature readings from Block (1) and that from the porous medium (2), two equations are generated which can be solved to determine α as well as $T_{2\,in}$ i.e. surface temperature of the porous medium at t = 0. The porous medium temperature T_2(z, 0) beneath the Block was measured at the depths of 2, 4, 8, 16 and 32 mm.

From eq. (2) $a_i = \frac{\lambda_i}{C_i}$ therefore $\sqrt{a_i} = \frac{\sqrt{\lambda_i}}{\sqrt{C_i}}$

$$\sqrt{a_2} = \frac{\sqrt{\lambda_2}}{\sqrt{C_2}} = S \times \frac{\sqrt{\pi}}{2} \times \frac{1}{E_2} \times \left(1 + \frac{1}{\alpha}\right) \qquad (9)$$

where S is the slope of graph $T_1(0,t)$ vs $\sqrt{t}$ (Schneider, 1969). As the temperature gradient E_2 (the slope of the graph of temperature T_2 (z,0) vs the depths) in the upper sample layer is known, we can calculate

Block Apparatus Fabrication

Block method device was fabricated as shown in (Fig. 1) from Perspex (10 x 10 x 4 cm) with λ_p = 0.18568 W/mK, C_p = 1.728 x 10^{-4} J/m^{3}K. Copper- constantan thermocouples were on the ground face and at several depths (2, 4, 8, 16 and 32 mm) inside the block. At these different heights in the block, the initial temperature at the instant t = 0 is measure with thermocouple. The block with an insulation cover (2.54 cm - thick Styrofoam) is placed in a thermostat.

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After a few hours, the temperature at the surface of the block and within it was recorded for a short time to measure the initial temperature of the block and ensure a uniform temperature. After removing the insulation plate covering the lower surface, the block is quickly placed on the sample surface, the time of contact being taken at t = 0 while the contact temperature would be registered for about 5 minutes.

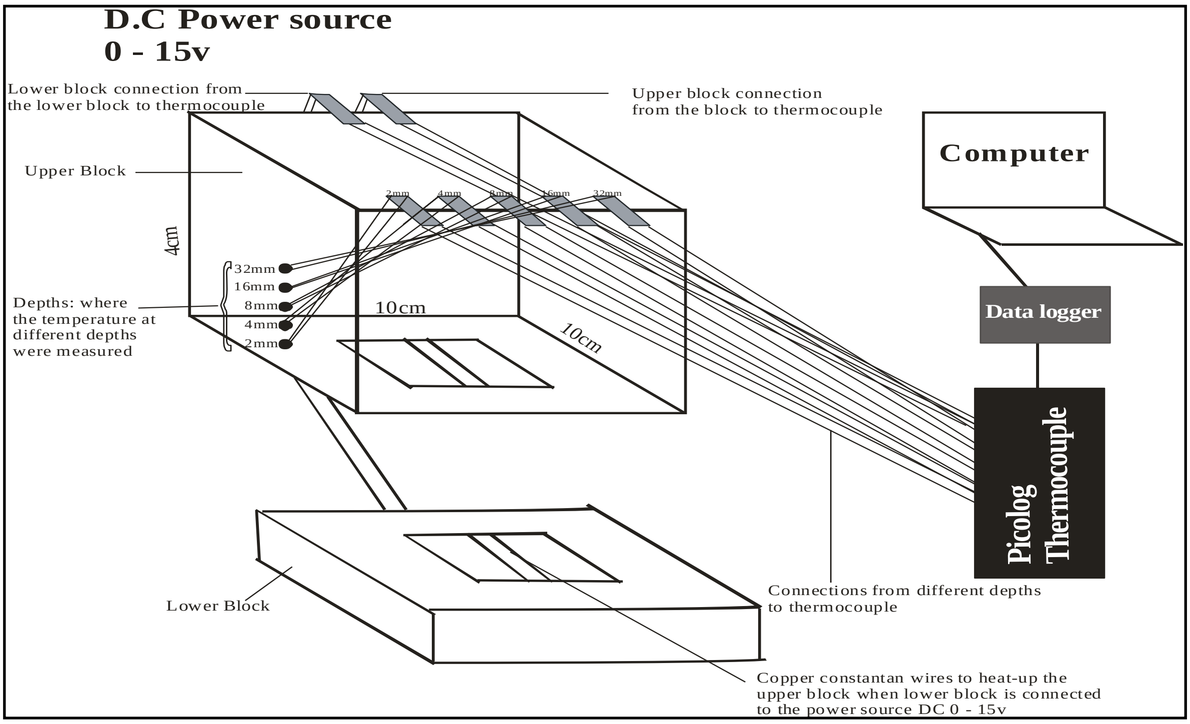

Figure 1: Set-up diagram of Block Apparatus

Samples Collection

Soil samples used in this work include; clay, loam and sand (fig. 2 a,b & c) represent topsoil samples and because of the relative abundance, the soil were collected around Abeokuta, South - West Nigeria (Figs. 2 a, b & c). The area comprising rocks of the Precambrian basement which are generally considered to be of Paleocene age (Adegoke, 1977).

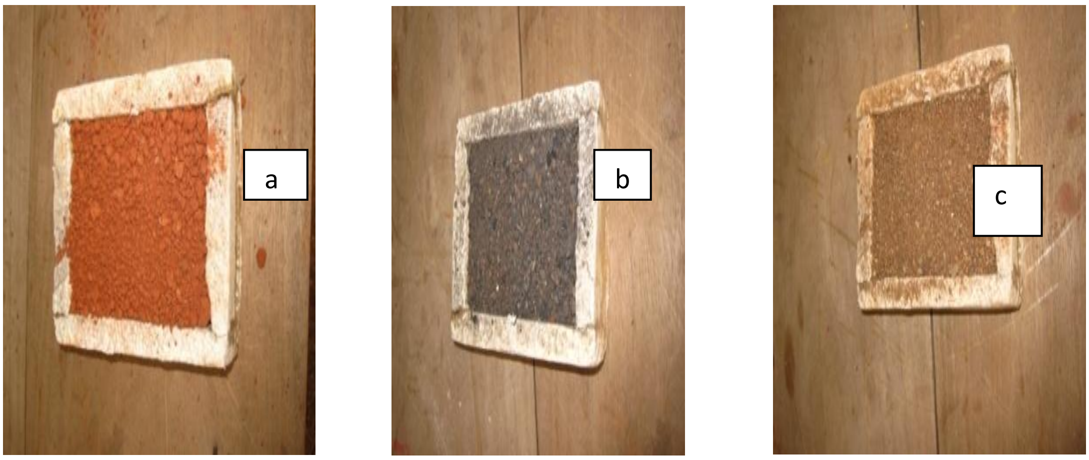

Figure 2: The topsoil samples

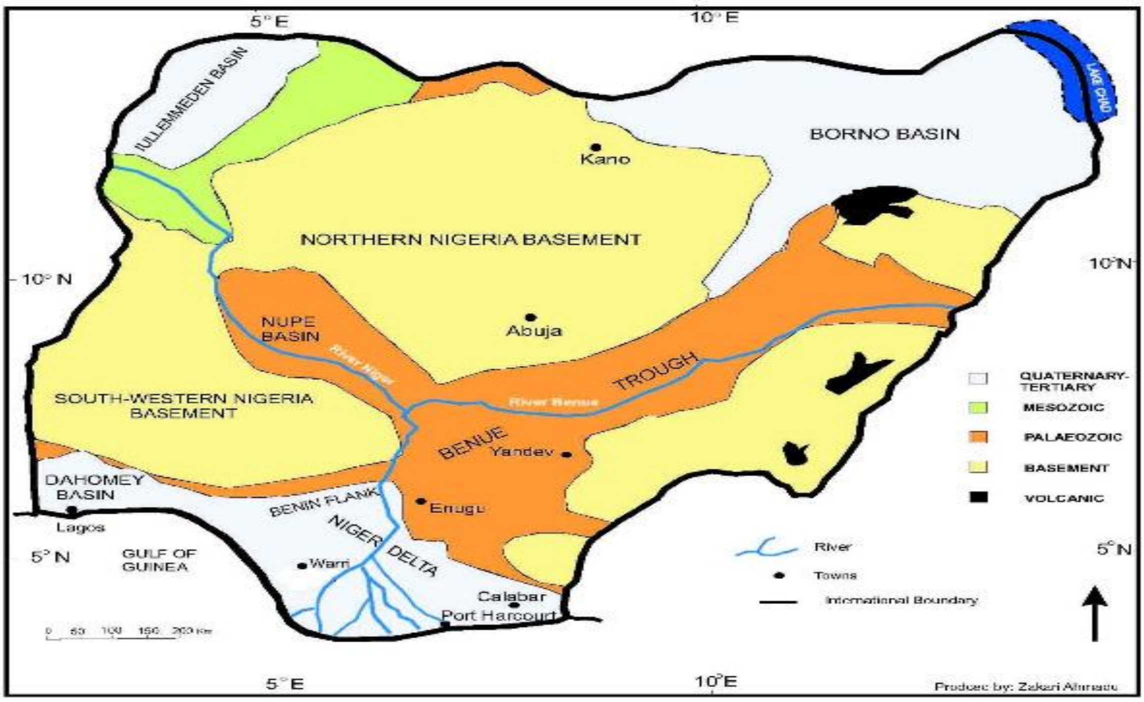

Figure 3a: A Map of Nigeria showing area of geological survey.

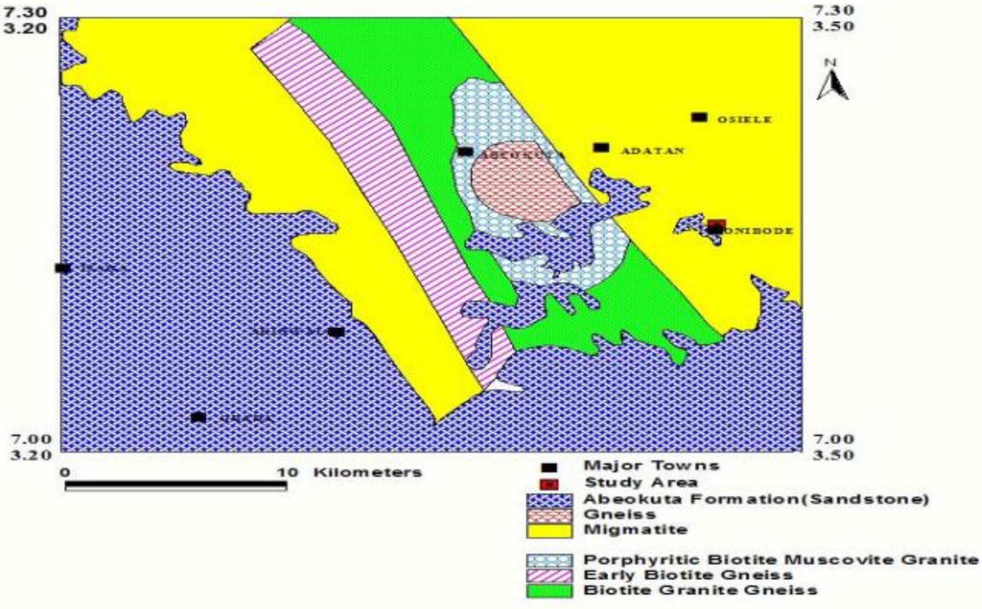

Figure 3b: Study area map(Muotoh *et al.*, 1988)

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RESULTS

Table 4.1 shows results for Block, KD2 methods and standard values. BO and BW in the tables represent block measurement without TIM and with TIM, and KO and KW represent KD2 measurement without TIM and with TIM respectively.

Lifting the equation $a_i = \frac{\lambda_i}{c_i}$ (9)

Then $\alpha = \frac{\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1}}$

On squaring both sides of Equation (9)

yields $\sqrt{a_i} = \frac{\sqrt{\lambda_i}}{\sqrt{C_i}}$ (10)

Table 1: Thermal conductivities results for all samples

Samples	**Block Exp. without TIM λ_{BO}**	**Block Exp. with TIM λ_{BW}**	**Difference $\lambda_{BW-}\ \lambda_{BO}$**	**% of difference**	**KD2 without TIM λ_{KO}**	**KD2 with TIM λ_{KW}**	**Difference $\lambda_{KW-}\ \lambda_{KO}$**	**%of difference**	**Standardrange values (Kappelmayerand Heanel, 1974 and R.C Zeller (1971)**
Clay soil **Thermal conductivity (λ) (Wm/K)**	0.68	0.85	0.17	20	0.66	0.84	0.18	21.4	0.15 – 1.8 W/mk
Sand soil **Thermal conductivity (λ) (Wm/K)**	0.34	0.39	0.05	12.8	0.28	0.33	0.05	15.2	0.15 -0.25 W/mk
Loamy soil **Thermal conductivity (λ) (Wm/K)**	0.18	0.34	0.16	47.1	0.17	0.30	0.13	43.3	0.15 – 1.8 W/mk

Clay: Thermal conductivity λ of clay increased from 0.68 to 0.85 W/mK with 20% difference for the block method with TIM and from 0.66 to 0.84 W/mK with 21.4% difference for the KD2. Thermal conductivity of clay is low because of low compactness of particles and high content of air within which allows lower transfer of heat.

Sand: Thermal conductivity λ of sand increased from 0.34 to 0.39 W/mK with 12.8% difference for the block method with TIM and from 0.28 to 0.33W/mK with 15.2% difference for the KD2. Thermal conductivity of sand is low because of low compactness of particles and high content of air within which allows lower transfer of heat.

Loam: Thermal conductivity λ of loam increased from 0.18 to 0.34 W/mK with 47.1% difference for the block method with TIM and from 0.17 to 0.33 W/mK with 43.3% difference for the KD2. Thermal conductivity of loam is low because of low compactness of particles and high content of air within which allows lower transfer of heat.

A different in porosity along with differences in composition also explains the lower thermal conductivities of clay, sand and loam. Clay, sand and loam which are more porous (less dense) has lower thermal conductivities. Decrease in thermal conductivities from clay to sand and to loam implies the rate of flow of heat to be higher in clay than in sand and in loam due to the high compactness of particles in clay, then sand and loam. The higher the compactness of particles of a material, the greater the rate of flow of heat and hence the greater the thermal conductivity.

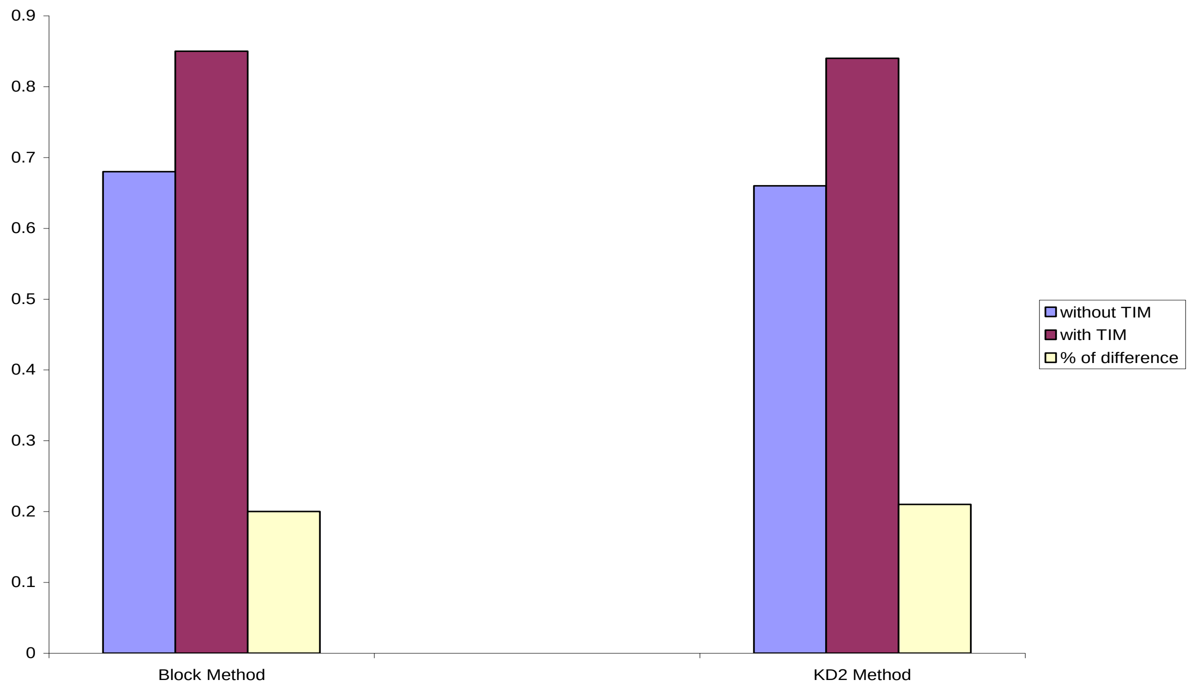

Figure 4(a): Bar chart of Clay thermal conductivity for Block and KD2 method

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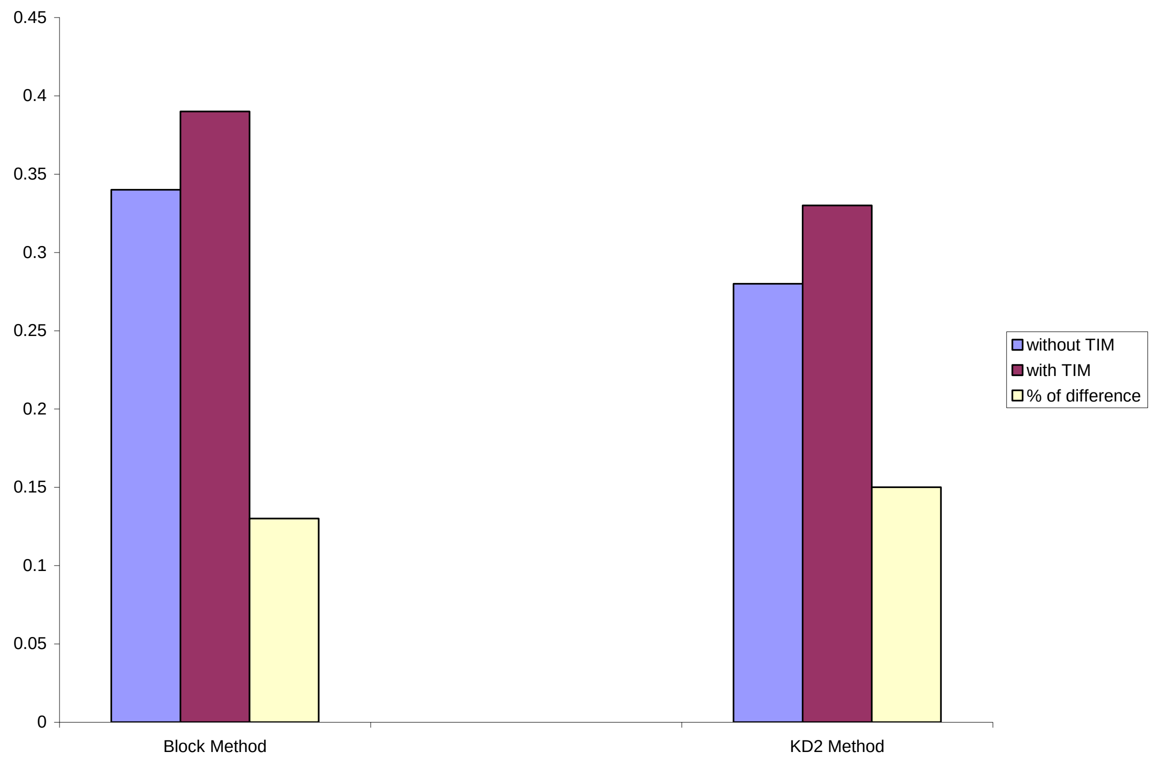

Fig. 4(b): Bar chart of Sand thermal conductivity for Block and KD2 methods

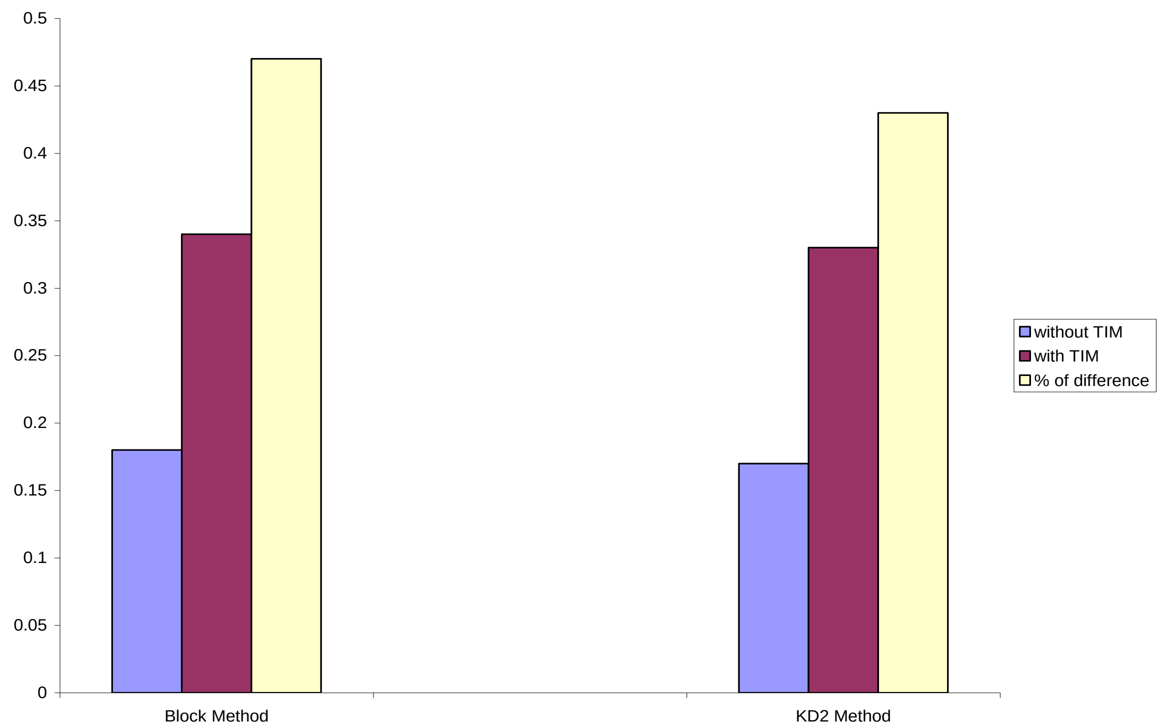

Figure 4(c): Bar chart of Loam thermal conductivity for Block and KD2 methods

DISCUSSION

Test of significance was carried out between the two methods, block and KD2 with TIM and without TIM through the analysis of variance (ANOVA) using Fisher's Protected Least Significant Difference. Thermal conductivities determined for clay, sand and loam are presented with and without the use of TIM , shown in Table 1 for Block method and KD2 thermal properties analyzer were used for the analysis. Thermal conductivities with and without TIM were tested statistically using (FPLSD) and it was found that using TIM was significant at $P > 0.5$ in correcting contact resistance.

Illustrative comparison of thermal conductivities (with and without the use of TIM) of all samples for Block and KD2 Analyzer measurements with percentage of difference are shown in Figs. 4 a, b &c. This is to show the relationship between the results when TIM was not applied and when TIM was applied for the Block and Line source (KD2) methods. This implies that, for all charts shown, thermal conductivity determined (Red) with the use of TIM always higher than the one determined without the use of TIM (Blue) for the Block and line source method. The percentages of difference for the two methods are almost the same, which implies that the block method results compare well with line source method.

Thermal Block technique was applied on clay, sand, and loam with a view to measuring thermal conductivity. Errors associated with contact addressed using thermal interface materials. Measurements from KD2 thermal analyzer was used to validate the results from block measurements and results compared well. Thermal Conductivities results for clay, without the use of TIM for Block and KD2 analyzer compare close well with the standard values (table 1). The values determined with the use of TIM are greater than those values without the use of TIM for both Block and KD2 methods, thus justifying the capacity of TIM to correct the contact errors on the surface. A similar trend was observed for all samples. Thermal Interface materials improved values of Thermal Conductivity of soil samples. Thermal conductivity of clay, sand and loam increased from 0.68 W/mK to 0.85 W/mK, 0.34 W/mK to 0.39 W/mK and 0.18 W/mK to 0.34 W/mK respectively.

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