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Effect of Additives on the Thermal Conductivity of Loamy Soil in Cross River University of Technology (CRUTECH) Farm, Calabar, Nigeria

C. O. Edet[1*], P. O. Ushie[1] and C. M. Ekpo[1]

[1]Department of Physics, Cross River University of Technology, Calabar, Nigeria.

Authors' contributions

This work was carried out in collaboration between all authors. Author COE designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors POU and CME managed the analyses of the study. Author CME managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Effect of Additives on the Thermal Conductivity of Loamy Soil in CRUTECH farm, Calabar, Nigeria was investigated. The loamy soil and various manure samples was measured in simple ratio of 3 to 1 and thoroughly mixed, then dissolved in water and air dried using an oven. A Lee's disc apparatus was used to determine the thermal conductivity of the various samples (Loamy Soil, loamy soil + Urea, Loamy Soil + Cow dung, Loamy Soil + Poultry dung and Loamy Soil + NPK). The results reveal that at no moisture content (after heating), loamy soil sample without additive has a thermal conductivity of 0.096W/m K and also thermal conductivity values varied with addition of Cow dung (0.135 W/m K), poultry dung(0.231 W/m K), urea(0.140 W/m K) and NPK(0.108 W/m K). It clearly shows that the thermal conductivity of loamy soil increases with additives. It was also observed that loamy soil mixed with fertilizer produced a thermal conductivity higher than loamy soil mixed with organic manure. Therefore farmers are advised to always dope soil in their farmland with (organic or inorganic manure), this will improve yield, since plants growth are influenced by the microclimate which is influenced by thermal properties of soils.

Keywords: Additives; loamy soil; thermal conductivity; organic and inorganic manure.

**Corresponding author: E-mail: collinsokonedet@gmail.com, collinsedet@crutech.edu.ng;*

1. INTRODUCTION

The uppermost soil layer of the earth's crust provides support and nutrients for plant growth. Heat conduction is the transfer of heat from one part of a system at high temperature to another part of the same system at low temperature. The conduction process takes place at the molecular level and involves the transfer of energy from the more energetic molecules to those with lower energy levels. Heat conduction in many materials can be visualized as the result of molecular collision. The conduction of heat occurs only if there is a difference in temperature between two parts of the conducting medium. Heat flow through any soil depends on the thermal properties of the soil [1].

The thermal conductivities of specific soil constituents differ widely. Hence the space-averaged thermal conductivity of a soil depends on its mineral composition and organic matter content as well as the volume composition of water and air [2]. In agriculture, microbial activity, seed germination, seedling emergence and growth, root proliferation, root elongation and root enlargement are influenced by the microclimate which influences thermal properties of soils [3,4]. The thermal conductivity of a soil depends on two broad groups of factors; those which are inherent to the soil itself, and those which can be managed or controlled, at least to a certain extent, by human management. Those factors or properties that are inherent to the soil itself include the texture and mineralogical composition of the soil. While those that can be managed externally include soil moisture content and soil management [5]. Soil composition is seldom uniform in depth; hence thermal conductivity is generally a function of depth as well as of time. It also varies with temperature, but under normal conditions this variation is ignored [6]. Thermal conductivity is sensitive not only to the mineral composition of a soil but also to the sizes, shapes, and arrangements of soil particles. The conductivity and volumetric heat capacity increase with water content so also the diffusivity. For mineral soils, the thermal diffusivity increases with soil moisture content at low water contents and then gradually decreases with increasing soil moisture contents at high water contents [7]. Soil thermal properties are required in many areas of engineering, agronomy, and soil science, and in recent years' considerable effort has gone into developing techniques to determine these properties. Seed germination, seedling emergence, and subsequent stand establishment are influenced by the microclimate [8]. Thermal properties of soils play an important role in influencing microclimate [3,9].

The investigation of these thermal properties can have significant practical consequences such as evaluation of optimum conditions for plant growth and development and can also be utilized for the control of thermal-moisture regime of soil in the field [10].

The ability to monitor soil thermal properties is an important tool in managing the soil temperature regime to affect seed germination and growth. While related to soil temperature, it is more accurately associated with the transfer of heat throughout the soil, by radiation, conduction and convection. Plants processes such as root growth or germination do not occur until the soil reaches certain temperature depending on the particular plant. Another plant process adversely affected by cold temperature is transport of nutrients and water. A better understanding of how different soils warm up would benefit agriculture by allowing for better planning of planting of crops [11].

It has been analyzed that the use of different natural and recycled aggregates as main constituents in cement-based mortars [12]. Their results showed that all mixes fulfill the minimum consistency and strength requirements. The use of any of the aggregates proposed improves the thermal conductivity compared to the cement mortar on its own, independently of the proportion used. Limestone sand, silica sand and electric arc furnace slag enhance the thermal conductivity of the grout as its proportion of use increases.

It has been noted that Backfill materials play an important role in improving the thermal performance of geothermal heat exchangers [13]. A thermal probe tests was conducted to measure the thermal conductivity of sand-bentonite mixtures under different conditions. Based on microscopic observations, the mechanism of bentonite affecting heat conduction between the sand grains was analyzed. Experimental results showed that the thermal conductivities of sand-bentonite mixtures increased gradually with increasing saturation and varied weakly when the saturation was over 80%. At nearly saturated state, the thermal conductivity of sand-bentonite mixtures first increased with increasing percentage of bentonite by dry mass, then reached a peak at the range of 10-12%, beyond which the thermal conductivity decreased quickly.

The purpose of this work is to investigate the effect of additives (i.e. NPK, Urea, Poultry dung, and Cow dung) on the thermal conductivity of loamy soil gotten from CRUTECH farm. We seek to know if the thermal conductivity of the soil increases or decreases with addition of these additives.

2. THEORY

Soil temperature is determined by a number of factors, some of which include the location characteristics and thermal physical properties of the soil samples. The amount of radiant energy absorbed or reflected depends on the material coloration. The proportion of energy absorbed causes changes in the temperature of the soil samples. Thermal radiation or radiant heat emitted by hot bodies is electromagnetic waves containing a wide range of wavelengths. This energy absorbed by the surface may be used in:

(a) Heating of air outside the rock or soil surface
(b) Increasing the surface temperature,
(c) Heating the interior layer of the soil, or
(d) Radiating to the atmosphere [14].

2.1 Theoretical Framework

The rate of radiant energy absorptivity or reflectivity on any materials depends on its colour composition. This energy absorbed causes the changes in the temperature of the material. The absorbed energy has its application in increasing the surface temperature, heating the air outside the soil, heating the interior layers of the soil and radiativity to the atmosphere [15].

Temperature variations with thickness of solid materials depend on the TC (Thermal Conductivity), SHC (Specific heat capacity), TA (Thermal absorptivity), and diffusivity of the material. These properties determine whether or not the material can be used as a heat conductor or insulator. We can treat the samples under investigation as an ideal one dimensional heat transfer problem, because the heat flow in any solid material is usually expressed by one dimensional unsteady heat conduction equation [16], and beyond this the material under investigation fits in. The simplest conduction heat transfer can be described as "one dimensional heat flow" depicted in Fig. 1, In this situation, the heat flows into one face of the object and out of the opposite face with no heat loss (flow) at the sides of the object. The surfaces 1 and 2 are held at constant temperature. Clearly, "in one dimensional heat flow," the temperature of an object is a function of only one variable, namely the distance from either face of the object (face 1 or 2).

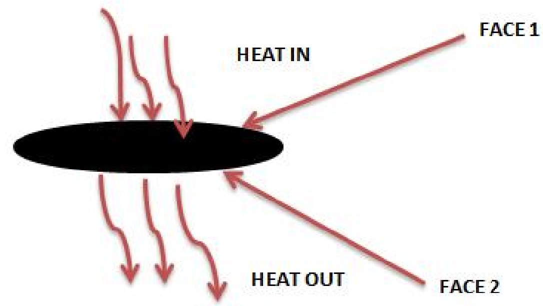

Fig. 1. One-dimensional heat flow

The sample will follow the general time dependent one dimensional heat transfer equation governed by Fourier's law [17],

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{\rho c}{k}\frac{\partial T(x,t)}{\partial t} \quad (1)$$

For a semi-infinite, homogeneous solid with constant thermal properties, Equation (1) can be solved when the boundary conditions at the material surface is known on both sides of the wall, and adopting the two boundary conditions in accordance with Newton's law, and also using the initial conditions (0, *t*), the energy balance equation follows Newton's law at the material surface [18]

$$\begin{aligned} -k\left(\frac{\partial T(0,t)}{\partial x}\right) &= h_e(T_{sa} - T_e) \\ -k\left(\frac{\partial T(0,t)}{\partial x}\right) &= h_i(T_i - T_m) \end{aligned} \quad (2)$$

where h_e and h_i are the heat transfer coefficients on the exterior and the interior surfaces of the wall, respectively, T_e and T_i correspond to the exterior (*x* = 0) and interior (*x* = *L*) surfaces temperatures of the wall, respectively. These two equations balance the heat transfer between the interior and exterior of the soil. The parameter is expressed as [19,20].

$$T_{sa} = T_{atm} + \propto I\epsilon\Delta R \quad (3)$$

is known as the solar temperature including the heat gain due to solar radiation absorption; *k* is the thermal conductivity of the material; T is the temperature of the material; h is the heat transfer coefficient at the surface of the material; T_{atm} is the atmospheric air temperature; α is the solar radiation absorptivity at the surface; I is the intensity of solar radiation; ϵ is the long wave emissivity of the surface; and ΔR is the difference between the incident long wave radiation and the radiation emitted from the surface. The general solution of the one dimensional heat conduction equation (assuming T is finite when $x \to \infty$) may be written as,

$$T(x,t) = A_0 \sum_{m=1}^{\omega} A_m \exp\left(i(m\omega t + \delta_m x\right) \quad (4)$$

where $\delta_m = m^{1/2}\alpha(1-i)$; $\alpha = \left(\omega\rho c/_{2k}\right)^{1/2}$, c is the specific heat capacity of the material; ρ is the density of the material, and $\omega = 2\pi/T$ [21] and [22]. Equation (4) gives the dependence of material temperature with thickness on the periodic variation of temperature at the surface. T_A can be expressed as Fourier series,

$$T(x,t) = a_0 + \sum_{m=1}^{\infty}\left(a_{m1}\cos(m\omega t) + a_{m2}\sin(m\omega t)\right) \quad (5)$$

$$a_0 + \sum_{m=1}^{\infty} B_m \exp\left(i(m\omega t - \delta_m)\right) \quad (6)$$

Substituting for $\mathrm{T(x,t)}$ from Equation (4) and for T_{SA} from Equation (5) and (6) into Equation (2) and considering the real part [23].

$$T(x,t) = a_0 + \sum_{m=1}^{\infty} B_m \exp\left(i(-m^{1/2}\alpha x\right)\cos\Big(m\omega t - m12\alpha x - \delta m - \beta m \quad (7)$$

Where $B_m = a_m\left(\left(1+m^{1/2}\mu\right)^2 + m\mu^2\right)^{-1/2}$

$$\mu = \frac{Ka}{h} = \frac{\left(k\omega\rho\frac{c}{2}\right)^{1/2}}{h} \quad (8)$$

$$B_m = \tan^{-1}\left(\frac{m^{1/2}\mu}{1+m^{1/2}\mu}\right) \quad (9)$$

and a_0 represents the average daily material temperature . The daily temperature variation at different depths of the material is given by Equation (7) with $\beta_m = 0$, $\omega = 2\pi/24$ hr, $B_m = a_m$. Equation (7) is modified to obtain the following convenient form [24,15],

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos\left[\omega\left\{(t-t_0) - \frac{\alpha x}{\omega}\right\}\right] \quad (10)$$

Where A_s is the daily temperature amplitude at the surface of the sample, *i.e.* at x = 0, t is the time of the day in hours, x is the coordinate through the thickness of the sample, t_0 is the time of minimum temperature at the surface in hours, α is the thermal absorptivity $(m)^{-1}$, T_m is calculated from the hourly surface temperature average $T_{hss}(C)$ as

$$T_m = \sum_{m-1}^{24}(T_{hss}/24) \quad (11)$$

Thus, on a 24 hour period, Equation (10) takes the form,

$$T(x,t) = T_m - A_s \exp(-\alpha x)\cos\left[\frac{2\pi}{24}\left\{(t-t_0) - \frac{12\alpha x}{\pi}\right\}\right] \quad (12)$$

2.2 Thermal Conductivity

Thermal conductivity is defined as the coefficient which multiplies the temperature gradient to give the rate of heat transfer by conduction expressed in heat energy crossing unit area in unit time [25]. When the steady state has been attained the rate at which heat is conducted across the soil samples disc, it is equal to the rate at which it is emitted from the exposed surfaces of the metal slab. If k is the thermal conductivity of the soil samples disc, A its Area, d its thickness, and ΔT is the temperature difference [26],

$$\frac{\Delta Q}{\Delta t A} = -k\frac{\Delta T}{\Delta x} \quad (13)$$

$\frac{\Delta Q}{\Delta t A}$ = Power per unit area transported
$\frac{\Delta T}{\Delta x}$ = Temperature gradient
k = Thermal Conductivity

3. MATERIALS AND METHODS

3.1 Experimentation

3.1.1 Samples collection and preparation

Soil sample used for the experiments was collected from CRUTECH farm area in Calabar, Cross River State, Nigeria. The soil sample was collected at depths of 0 – 20 cm beneath the earth surface and put in different labeled containers as shown in Fig. 2. They were then air dried using an oven for ten minutes at a temperature of 50°C to remove the moisture content and each of the samples were molded into a disc shape using an aluminum rings designed for this purpose. The samples were afterwards sun dried on the floor for one week to solidify and then stored in containers.

Dry samples were used to avoid the problem of redistribution of water under the influence of temperature gradient. Thermal conductivities were determined for each of the samples using the steady state method. Lee disc apparatus for bad conductor was modified and adapted for use. At the steady state the heat conducted across the soil sample is equal to the rate at which it is emitted from the exposed surface.

The loamy soil and various manure samples was measured in simple ratio of 3 to 1 and thoroughly mixed. The mixture was molded into a circular disc, dried to constant mass and carefully shaped with a diameter, d (88.0mm) and thickness x (5.0 mm). The thermal conductivity of each sample was determined using Lee's apparatus as shown in Fig. 3. Each sample in turn was sandwiched between the cylindrical hollow brass base and brass slab; and the arrangement was fitted to the steam chest of Lee's apparatus. Steam was passed into the apparatus and temperatures T_1 (°C) of the brass slab and T_2 (°C) of the brass base were recorded at steady state. The experiment was repeated three times and the mean temperatures T_1 and T_2 determined.

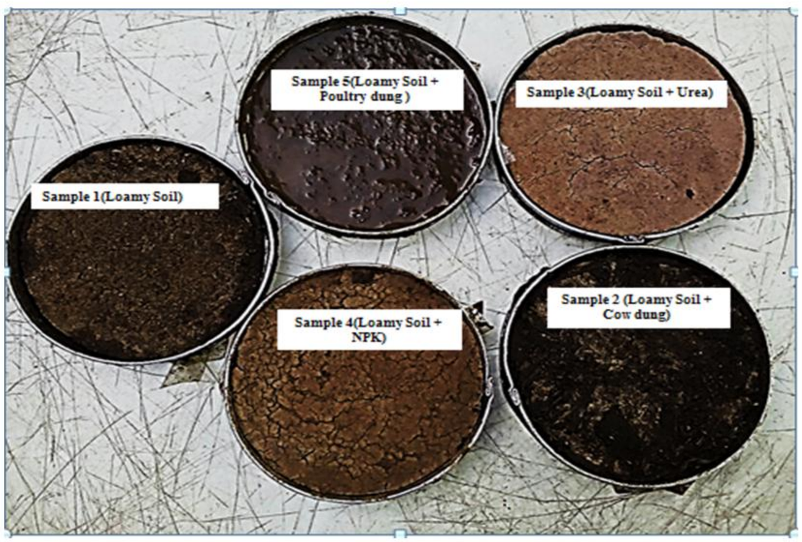

Fig. 2. Samples with labels in aluminum rings

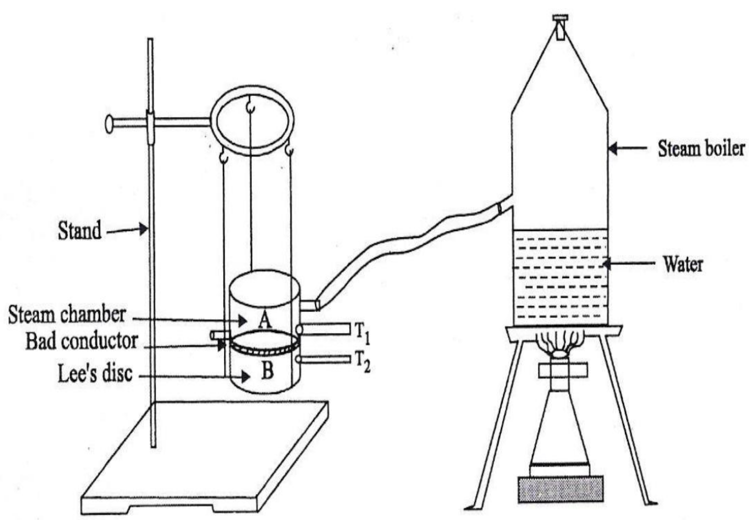

Fig. 3. Lee's apparatus setup and the experimental specimen in the form of a disc (bad conductor)

Table 1. Thermal conductivity of various samples

Samples	Thermal conductivity ($Wm^{-1}K^{-1}$)			
	1st Reading	2nd Reading	3rd Reading	Mean
Sample 1(Loamy Soil)	0.096	0.097	0.095	0.096
Sample 2(Loamy Soil + Cow dung)	0.135	0.136	0.135	0.135
Sample 3(Loamy Soil +Urea)	0.231	0.230	0.232	0.231
Sample 4(Loamy Soil+ NPK)	0.140	0.142	0.139	0.140
Sample 5(Loamy Soil + Polultry Dung)	0.108	0.109	0.108	0.108

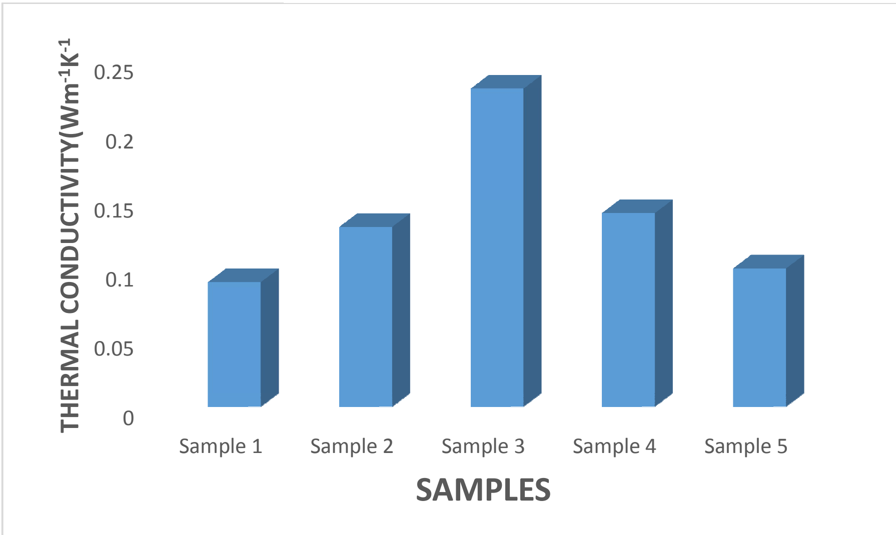

Fig. 4. Bar chart showing sample's thermal conductivity distribution

4. RESULTS AND DISCUSSION

Table 1 shows the data obtained for each sample. The results in Fig. 4 reveal that at no moisture content, loamy soil sample without additive has a thermal conductivity of 0.096 W/m K. It also shows that thermal conductivity values vary with addition of Cow dung, poultry dung, urea and NPK. Sample 3(Loamy Soil + Urea) gives a thermal conductivity of 0.231W/m K and this was the highest. It was equally observed that loamy soil mixed with inorganic manure (Urea and NPK) produced a thermal conductivity higher than loamy soil mixed with organic manure (Cow dung and Poultry dung). The results obtained in this study agree with earlier studies by [12] and [13], which also dealt with improvement of materials by introducing additives.

5. CONCLUSION

Effect of additive on the thermal conductivity of loamy soil was investigated. It was found that some of the properties were improved upon with addition of Cow dung, poultry dung, urea and NPK but was lower when the loamy soil sample was without an additive. Hence, the thermal conductivity of the soil under investigation improved with additive. Farmers are advised to always dope soil in their farmland with (organic or inorganic manure), this will improve yield, since plants growth are influenced by the microclimate which is influenced by thermal properties of soils. More so, farmers are also advised to dope the soil with more inorganic manure (urea and NPK) because as observed in Table 1 and Fig. 4 respectively, this improved the thermal conductivity of the soil more than the organic manure.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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