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# Measurement of Thermal Conductivity and Specific Heat Capacity of Three Major Geomorphological Units in Akwa Ibom State, Nigeria

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***Authors' contributions***

*This work was carried out in collaboration between all authors. Authors STE and ESA performed the laboratory experiment and analysis, wrote the first draft of the manuscript and managed literature searches. Author EOJ helped in the literature searches and final draft of the manuscript. All authors read and approved the final manuscript.*

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## ABSTRACT

The thermal conductivity (k) and the specific heat capacity (C) of some samples collected from three major landforms in Akwa Ibom State, Nigeria; namely Beach Ridge Sand (BRS), Coastal Plane Sand (CPS), Sandstone/Shale Hill Ridges (SHR) were measured. Results show that an increase in C of SHR and BRS samples taken from different locations gives rise to decrease in k. The C of the area under study falls within the range 1813.64 $Jkg^{-1}K^{-1}$ to 3313.24 $Jkg^{-1}k^{-1}$ while the soil thermal conductivity was between the range 0.272 $Wm^{-1}K^{-1}$ to 0.451 $Wm^{-1}K^{-1}$. The C of the soil samples has great effect on crop and construction works.

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## 1. INTRODUCTION

The study of soil properties is very important and useful to determine the soil thermal conductivity. 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 the body at high temperature to another part of the same body 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 [1]. The conduction of heat occurs only if there is a difference in temperature between two parts of the conducting medium [2]. Heat flow through any soil depends on the thermal properties of the soil. Variation in temperature with thickness of the soil determines whether the soil can be used as heat source. The prediction of temperature at various thicknesses at any given time of the day throughout the year is an important tool in the design of a construction work. Thermal properties of soil samples involve many variables which may be complicated. Such variables include the soil texture, structure and composition parameters. Similar studies of soil properties in recent years include comparison of the thermal properties of brick samples for a passively cooled building design [3] and thermal response of different rock samples for a passively cooled building design [4].

## 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 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 [5].

### 2.1 Specific Heat Capacity

Specific heat capacity of a substance is the quantity of heat required to raise the temperature of unit mass (kg) of the substance through unit temperature (1℃ or 1K). It is observed experimentally that the quantity of heat (Q) received by a body is proportional to its mass (M) and temperature change ($\Theta_2$ - $\Theta_1$) and also, depends on the nature of the material making the body. Mathematically, it is expressed as:

$$Q = MC(\Theta_2 - \Theta_1) \quad (1)$$

$$\text{Also, } C = Q / M(\Theta_2 - \Theta_1) \quad (2)$$

where Q is the quantity of heat, M is the mass of the sample (body) in kg,($\Theta_2$ - $\Theta_1$) is the temperature change in ℃ or K, C is the constant of proportionality which depends on the nature of the body [6]. The unit of C is $Jkg^{-1}K^{-1}$.

Heat gained by calorimeter + sample + cold water =

$$M_cC_c(\theta_3 - \theta_1) + M_sC_s(\theta_3 - \theta_1) + M_{cw}C_w(\theta_3 - \theta_1) \quad (3)$$

Heat lost by the hot water

$$= M_{nw}C_w(\theta_2 - \theta_3) \quad (4)$$

Equating 3 and 4 gives the working equation for specific heat capacity:

$$M_{nw}C_w(\theta_2 - \theta_2) = M_cC_c(\theta_3 - \theta_1) + M_sC_s(\theta_3 - \theta_1) + M_{cw}C_w(\theta_3 - \theta_1) \quad (5)$$

The specific heat capacity is then:

$$C_s = \frac{M_{nw}C_w(\theta_2-\theta_3)-[M_cC_c+M_{cw}C_w](\theta_3-\theta_1)}{M_S(\theta_3-\theta_1)} \quad (6)$$

### 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 [7]. 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 C. If *k* is the thermal conductivity of the soil samples disc, *D* its diameter, *d* its thickness, and the readings of the thermometers $T_1$ and $T_2$ in the steady state are $\Theta_1$ and $\Theta_2$ (℃), then the rate at which heat is conducted across the disc of soil samples is

$$k = \frac{\pi D^2}{4} * (\frac{\theta_1-\theta_2}{d}) \quad (7)$$

If the mass of the metal slab *C* is *M*, its specific heat C, and the rate of cooling at $\theta_2$($^o$C) is $(\frac{d\theta_2}{dt})$ (obtained by drawing a tangent to the cooling curve at $\theta_2$), then the rate of loss of heat from the lower face and the sides of the slab *C* is

$$MC\ (\frac{d\theta_2}{dt}) \quad (8)$$

Hence equating (7) and (8) we have

$$k = \frac{\pi D^2}{4} * (\frac{\theta_1-\theta_2}{d}) = MC\ (\frac{d\theta_2}{dt}) \quad (9)$$

from which k may be determined [8]. Since by Newton's law of cooling, the rate of loss of heat is proportional to the excess temperature of a body over that of its surroundings, equation (9) above may be written as:

$k = \frac{\pi D^2}{4} * (\frac{\theta_1-\theta_2}{d})$ =const. $(\theta_2 - \theta_0)$ where $\theta_o$ is the air temperature [8].

Hence if for a specimen of another material of thermal conductivity *k'* and thickness *d'*, the steady state temperatures are $\theta_1$' and $\theta_2$', a comparison of the thermal conductivities of the two specimens can be obtained without the necessity of proceeding with the second part (cooling curve) of the experiment. It follows that, for a prescribed temperature gradient, the conduction heat flux augments with increasing thermal conductivity [7].

Heat conduction takes place only if there is temperature difference. Indeed, it is found experimentally that the rate of heat flow through a substance is proportional to the difference in temperature between its ends [1]. In steady state the heat conducted across the soil sample is equal to the rate at which it is emitted from the exposed surface [9]. In general, the thermal conductivity of a solid is larger than that of a liquid, which is bigger than that of a gas [7].

## 3. METHODS

### 3.1 Sample Collection and Preparation

Soil samples involved in the experiments were collected from three landforms in Akwa Ibom State. The landforms are: Beach Ridge Sand (BRS), Coastal Plane Sand (CPS) and Sandstone/Shale Hill Ridges (SHR). The soil samples were collected at depths of 0 – 15 cm beneath the earth surface and put in different labeled containers. They were then air dried in the Physics laboratory, University of Uyo, Nigeria to drive away the moisture content. With some water, the soil samples were made wet so that they could be molded into the desired shape. Each of the samples was molded into a disc shape using a plastic ring designed for this purpose. The samples were afterwards dried on the ground or floor to solidify and were then stored in containers. Six different soil samples were collected; locations and sources of collection are shown in Table 1.

**Table 1. Landforms and source of soil samples**

| Landforms | Location |
|---|---|
| Beach Ridge Sand (BRS 1) | Ikot Ibok, Eket LGA. |
| Beach Ridge Sand (BRS 2) | Ikot Akpan Mkpe, Onna LGA. |
| Coastal Plain Sand (CPS 1) | Ikot Akan, Nsit Ubium LGA. |
| Coastal Plain Sand (CPS 2) | Uniuyo Annex, Uyo LGA. |
| Sandstone/Shale Hill Ridges (SHR 1) | Ikpe Ikot Nkon, Ini LGA. |
| Sandstone/Shale Hill Ridges (SHR 2) | Ntak sInyang, Itu LGA. |

### 3.2 Measurement of Specific Heat Capacity

The following laboratory equipments were used during the analysis: weighing balance, thermometer, calorimeter, heat source, beaker, water, stop clock, soil samples (solid), thread, and logging material [8]. The calorimeter with stirrer was weighed and its mass was recorded as $M_c$. The solid was put into the calorimeter and weighed as $M_1$ and then the calorimeter was half filled with water. The calorimeter and the mixture were weighed and the mass was recorded as $M_2$. The initial temperature of the mixture was taken as $\theta_1$; the final temperature of the boiling water was taken as $\theta_2$, the hot water was poured into the calorimeter with the mixture and the change in temperature with change in time was recorded. The highest temperature of the mixture was recorded as $\theta_m$. Then, the specific heat capacity was calculated for each of the soil samples using equation 6 where;

$C_s$ = specific heat capacity of the sample
$M_{nw}$ = mass of hot water ($M_3$- $M_2$)
$C_w$ = specific heat capacity of water
$M_c$ = mass of calorimeter
$C_c$ = specific heat capacity of calorimeter
$M_{cw}$ = mass of cold water ($M_2$-$M_1$)

$M_s$ = mass of sample
$\Theta_1$ = initial temperature of mixture
$\Theta_2$ = temperature of hot water
$\Theta_3$ = final temperature of the mixture
$M_1$ = mass of calorimeter + sample
$M_2$ = mass of calorimeter + mixture
$M_3$ = mass of calorimeter + mixture + hot water

### 3.3 Calculations for Specific Heat Capacity

Using the experimental result of Table 2 and the working equation 6 for specific heat capacity, the experimental values of $C_s$ were calculated for all samples as CPS 1, whose results are shown in Table 4.

$M_{nw}$ = 0.06850kg

$M_c$ = 0.0545kg

$M_{cw}$ = 0.02326kg

$M_s$ = 0.02964kg

$C_w$ = 4200Jkg$^{-1}$K$^{-1}$

$C_c$ = 400Jkg$^{-1}$K$^{-1}$

$\theta_1$ = 29.5℃ + 275 + 275 = 302.5K

$\theta_2$ = 98.5℃ + 273 = 371.5K

$\theta_3$ = 71.55℃ + 273 = 34455K

$\theta_2 - \theta_3$ = 371.5 – 344.55 = 26.95K

$\theta_3 - \theta_1$= 344.55 – 302.5 = 42.05K

$$C_s = \frac{[0.06850 \, X \, 4200 \, X \, 27.36]-[(0.0545 \, X \, 400)+ (0.02326 \, X \, 4200)]41.64}{0.02964 \, X \, 42.05}$$

$$C_s = \frac{7871.472- 4975.64688}{1.246362}$$

$C_s$ = 2323.422$Jkg^{-1}$K$^{-1}$

Error in $C_s$ is given as:

$$\frac{\delta c_s}{c_s} = \frac{\delta m_{nw}}{m_{nw}} + \frac{\delta \theta}{\theta_2 - \theta_3} + \frac{\delta m_c}{m_c} + \frac{\delta \theta}{\theta_3 - \theta_1} + \frac{\delta m_{cw}}{m_{cw}} + \frac{\delta m_s}{m_s}$$

Error in mass = 0.00001 kg

$$\frac{\delta c_s}{c_s} = \frac{0.00001}{0.06850} + \frac{0.50}{27.36} + \frac{0.00001}{0.05450} + \frac{0.50}{41.64} + \frac{0.00001}{0.02326} + \frac{0.00001}{0.02964}$$

$\frac{\delta c_s}{c_s}$ = 0.03138
$\delta c_s$ = 2323.4222 x 0.03138

$\delta c_s$ = 72.908989 Jkg$^{-1}$K$^{-1}$

$c_s$ = (2323.42 $\pm$ 72.91) Jkg$^{-1}$K$^{-1}$

Also, $C_w$ = 4200 Jkg$^{-1}$K$^{-1}$ and $C_c$ = 400 Jkg$^{-1}$K$^{-1}$ while Θ is in K; by putting the above data in Table 2 into equation 8 we have the results in Table 3. Different materials absorb energy in different ways [10].

### 3.4 Measurement of Thermal Conductivity

The following laboratory equipments were used during the experiment: Lee's disc apparatus, thermometers, steam can, vernier caliper, strings, and retort stand with clamp, heat source and rubber tubing. The apparatus was suspended as shown in Fig. 1, below and with the flat surfaces of the horizontal discs. Steam passes through the cylinder A, and the temperatures indicated by the two thermometers $T_1$ and $T_2$ are read when the steady state has been reached after 30-60 minutes. $T_1$ and $T_2$ are then interchanged, and their temperatures are again read when steady state is reached. The cylinder A is then removed and a Bunsen flame is allowed to come in contact with the bottom surface of the slab C until $T_2$ records a temperature up to 10℃ higher than that recorded in the steady state. It is then allowed to cool, and readings of the temperature were taken at ½ - minute intervals until the temperature

**Table 2. Experimental values of each sample for the determination of specific heat capacity**

| Landforms / samples | $M_c$ (kg) | $M_s$ (kg) | $M_{cw}$ (kg) | $M_{nw}$ (kg) | $\theta_1$℃ | $\theta_2$℃ | $\Theta_3$℃ |
|---|---|---|---|---|---|---|---|
| BRS 1 | 0.0545 | 0.02556 | 0.02731 | 0.06238 | 29.5 | 98.5 | 69.58 |
| BRS 3 | 0.0545 | 0.04294 | 0.02587 | 0.05985 | 29.5 | 98.5 | 67.23 |
| CPS 1 | 0.0545 | 0.02964 | 0.02326 | 0.06850 | 29.5 | 98.5 | 71.55 |
| CPS 3 | 0.0545 | 0.02980 | 0.02021 | 0.07919 | 29.5 | 98.5 | 74.48 |
| SHR 1 | 0.0545 | 0.03322 | 0.02766 | 0.04254 | 29.5 | 98.5 | 61.14 |
| SHR 3 | 0.0545 | 0.03810 | 0.02834 | 0.05230 | 29.5 | 98.5 | 60.64 |

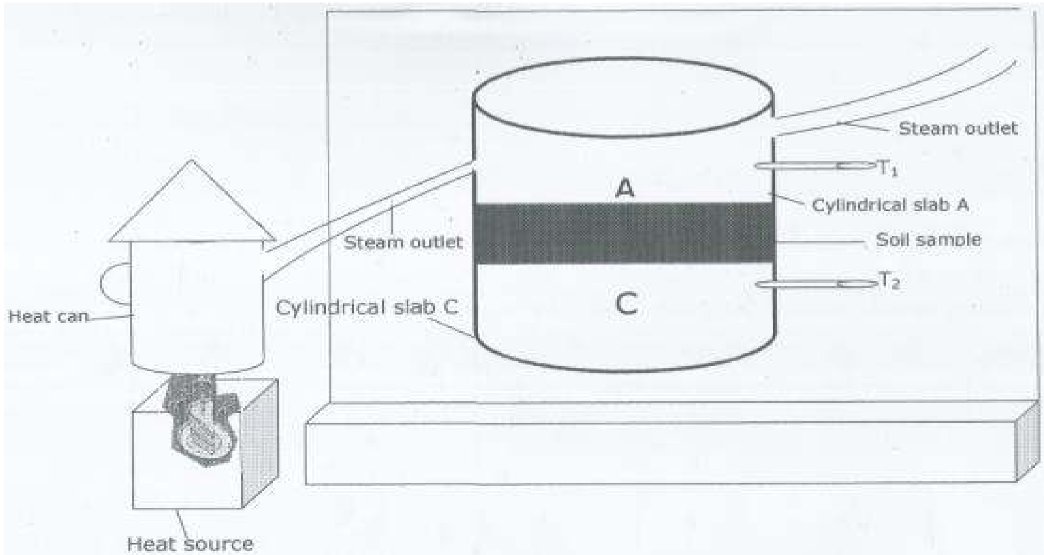


**Fig. 1. Determination of thermal conductivity of soil samples by Lee's Disc method**

drops to about 10℃ below the steady state temperature. The diameter of the soil sample disc was measured, its thickness was found using a screw gauge and the mass of the metal slab C was determined [8].

### 3.5 Calculations for Thermal Conductivity

The result for thermal conductivity was obtained by using equation 9. The method used here was applied to obtain the results for other samples as recorded in Table 4 the gradient is:

$$\frac{d\theta}{dt} = \frac{\theta_2 - \theta_1}{t_2 - t_1}$$

$\theta_2$ = 57.0℃ + 273 = 330k     $t_2$ = 135 seconds

$\theta_1$ = 40.0℃ + 273 = 311k     $t_2$ = 1410 seconds

Hence, $\frac{d\theta}{dt} = \frac{(330-313)k}{(135-1410)sec.} = \frac{17.0k}{-1275s}$

$$\frac{d\theta}{dt} = -0.01333ks^{-1}$$

To calculate the thermal conductivity k, from equation 16

$$k = \frac{mc\, d\theta/dt}{\frac{\pi D^2}{4}[\frac{\theta_1 - \theta_2}{d}]}$$

m = 0.52 kg, c = 400 $Jkg^{-1}K^{-1}$, π = 3.142, D = 0.0625 m,

d = 12.80 x $10^{-3}$m, $\theta_1$= 94℃ + 273 = 367K

$\theta_2$ = 51.5℃ + 273 = 324.5K,
$d\theta/dt$ = 0.01333 $K.s^{-1}$

Substituting the values to obtain k,

$$k = \frac{2.77264}{10.18791}$$

k ≈ 0.272W/Mk

Error in k is given as:

$$\frac{\delta k}{k} = \frac{\delta d\theta/dt}{d\theta/dt} + \frac{2\delta D}{D} + \frac{\delta\theta}{(\theta_1 - \theta_2)} + \frac{\delta d}{d}$$

Error in gradient, $d\theta$/dt = 0.00027℃/S

Error in diameter, D = $\frac{0.01}{2}$cm = 0.005cm = 5 x $10^{-5}$m

Error in temperature $\theta = \frac{1^0C}{2}$ = 0.05℃

Error in thickness, d = $\frac{0.001}{2}$cm = 0.0005cm = 5 x $10^{-5}$m

$$\delta k = k\,[\frac{\delta d\theta/dt}{d\theta/dt} + \frac{2\delta D}{D} + \frac{\delta\theta}{(\theta_1 - \theta_2)} + \frac{\delta d}{d}]$$

= 0.272 [0.02025 +0.0016 + 0.01176 + 0.00039]

$\delta k$ = 0.009 W/mK

$k$ = (0.272 ± 0.009) $Wm^{-1}K^{-1}$

## 4. RESULTS AND DISCUSSION

The results of the diameter of the soil sample disc were measured as 0.0625 m;

The thickness of the soil sample disc was 12.80 x $10^{-3}$m;

The mass of the metal slab C was 0.05254 kg;
Specific heat capacity of metal C (from table) is 400 $Jkg^{-1}K^{-1}$

The results for the thermal conductivity and the specific heat capacity were obtained as shown in table below.

Using the value of specific heat capacity C and thermal conductivity k; then, Pearson's correlation coefficient $\gamma = 1 - \frac{6\sum d^2}{n(n^2-1)}$ [11]; where n = 6 (number of soil samples), $d^2$ = 52, but $C_R$ - $k_R$ are correlation coefficient of specific heat capacity (C) and thermal conductivity (k).

Thus, $\gamma = 1 - \frac{6\sum d^2}{n(n^2-1)}$ = 1- $\frac{(312)}{6(35)}$ = -0.4857

By using the analysis of variance (ANOVA),

Null hypothesis ($H_N$): C = k; if $\gamma_{cal} > \gamma_{tab}$

Alternative hypothesis ($H_A$): $C \neq k$; if $\gamma_{cal} < \gamma_{tab}$

Where $\gamma_{cal}$ = calculated value of γ and $\gamma_{tab}$ = value of γ from correlation table. From correlation table [12]; with 6 degree of freedom $\gamma_{tab}$ at $\propto$ = 0.05 and $\gamma_{tab}$ = 0.8860.

Since $\gamma_{cal}$ = -0.4857 < $\gamma_{tab}$ = 0.8860, we upheld the alternative hypothesis and concluded that there is no significant difference in the C values of the three landforms observed in Akwa Ibom State.

**Table 3. Temperatures at steady state**

| | **Upper temperature $T_1$ ( 0℃ )** | **Lower temperature $T_2$ (0℃ )** |
|---|---|---|
| Before interchanging | 92.50 | 52.00 |
| After interchanging | 95.50 | 51.00 |
| Mean temperature | 94.00 | 51.50 |

**Table 4. Specific heat capacity and thermal conductivity of soil samples**

| **Landforms** | **Specific heat capacity ($Jkg^{-1}K^{-1}$)** | **Thermal conductivity ($Wm^{-1}K^{-1}$)** |
|---|---|---|
| BRS 1 | 1964.54 | 0.333 |
| BRS 2 | 1813.64 | 0.451 |
| CPS 1 | 2323.42 | 0.272 |
| CPS 2 | 2380.21 | 0.331 |
| SHR 1 | 2197.36 | 0.409 |
| SHR 2 | 3313.24 | 0.404 |

**Table 5. Results of the calculated $C_R$ – $k_R$ for each soil sample**

| **Landforms** | **C ($Jkg^{-1}K^{-1}$)** | **k($Wm^{-1}K^{-1}$)** | **$C_R$** | **$k_R$** | **$d=C_R-k_R$** | **$d^2$** |
|---|---|---|---|---|---|---|
| BRS 1 | 1964.54 | 0.333 | 2.00 | 3.00 | -1.00 | 1.00 |
| BRS 2 | 1813.64 | 0.451 | 1.00 | 6.00 | -5.00 | 25.00 |
| CPS 1 | 2323.42 | 0.272 | 4.00 | 1.00 | 3.00 | 9.00 |
| CPS 2 | 2380.21 | 0.331 | 5.00 | 2.00 | 3.00 | 9.00 |
| SHR 1 | 2197.36 | 0.409 | 3.00 | 5.00 | -2.00 | 4.00 |
| SHR 2 | 3313.24 | 0.404 | 6.00 | 4.00 | 2.00 | 4.00 |

$\sum d^2 = 52.00$

## 5. SUMMARY AND CONCLUSION

Different amounts of heat are absorbed by blocks of the same material if their mass is different and their temperature change is the same, if their mass is the same and their temperature change is different, or if they have different masses and undergo different temperature changes [13].

From Table 4 (above) SHR samples have the higher thermal conductivity closely followed by BRS and CPS. This shows that SHR samples tend to conduct heat at a higher rate than BRS and CPS. It is also observed that increase in specific heat capacity of SHR and BRS samples correspond to decrease in thermal conductivity while that of CPS show the opposite. In order to increase the temperature of an object one must increase the thermal energy of its molecules. We can do this by letting heat flow into the object from hotter object [14]. Evidently the larger the object to be heated, the greater the amounts of heat that must be supplied [15]. In a tropical region like Africa with a high level of incident solar radiation like in Nigeria, rock samples like those used for this work with high SHC and low thermal conductivity is recommended for the design of  bb civil or construction work.

## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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