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Research Article

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Effect of Saturation on Thermal Conductivity

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Abstract This paper investigates the effect of saturation on thermal conductivity. Thermal conductivity values were determined for six different soils samples in Akwa Ibom State, Nigeria. The thermal conductivity of soil samples was determined using Lee's steady state method. Correlation coefficient between saturation and thermal conductivity was also calculated for soil samples using Pearson's moment correlation coefficient method. Moisture content ranges from 57.55 to 69.90 %. Thermal conductivity ranges from 20.20 to 51.72 $Wm^{-1}k^{-1}$. Saturation level for the soil samples ranges between 0.101 and 0.117. The result revealed that saturation had positive but insignificant effect on thermal conductivity ($\beta = 43.10$, p>0.05).

Keywords Saturation, thermal conductivity, moisture content, soil, Akwa Ibom

1. Introduction

Saturation describes the amount of moisture content in a soil [1]. An increase in saturation results in increase in thermal conductivity. According to Van Genuchten (1980), saturation is defined as the water content for which the gradient becomes zero, and the saturated water content, which is equivalent to porosity. Saturation contains the largest concentration of the dissolved particles at a given conditions of pressure and temperatura [2]. Although it is possible, in certain circumstances, to bring about super saturation, such solutions or vapours are unstable and spontaneously revert to the saturated state [3]. Saturation is the quantity of water contained in a material such as soil (called soil moisture), rock, ceramics, fruit or wood. This is used in a wide range of scientific and technical areas, and is expressed as ratio, which can range from 0 (completely dry) to the value of the materials' porosity at saturation. It can be given on a volumetric or mass basis [4].

Saturation can be measured using laboratory methods that determine water content of a sample which include titrations, determining mass loss on heating or after freeze drying. Geophysical methods are also used to monitor soil moisture continuously in agriculture and scientific applications [5].

Saturation can also be measured using a satellite remote sensing method, which is used to estimate soil moisture based on the large contrast between the dielectric properties of wet and dry soil. The data from microwave remote sensing satellite such as: Windsat, AMSR-E, ERS-1-2, Metop/ASCAT are used to estimate surface soil moisture.

Thermal conductivity is the heat transfer rate per unit area proportional to the normal temperature gradient

$$\frac{q}{A} \ \alpha \frac{\partial T}{\partial X} \quad (1)$$

Inserting a proportionality constant and rearranging,

$$q = -KA\frac{\partial T}{\partial X} \quad (2)$$

Where q is the heat transfer rate, A is the area and $\partial T/\partial X$ is the temperature gradient in the direction of heat flow. The positive K constant is called thermal conductivity of the material, and the minus is inserted so that second principle of thermodynamics will be satisfied. Soil thermal conductivity varies with the mineral composition of the soil. However, a dramatic change in soil thermal conductivity occurs between the frozen and unfrozen states due to the higher thermal conductivity of Ice [6]. The investigation of the influence of saturation is accounted for in soil thermal conductivity prediction algorithms. This research work is aimed at determining the effect of saturation on soil thermal conductivity.

Theoretical Background of Saturation

An expression for saturation can be derived from the basic definitions of dry density, soil density, and moisture content as follows:

$$P_d = \frac{M_s}{V_T} \quad (3)$$

$$P_s = \frac{M_s}{V_s} \quad (4)$$

Where M_s is the mass of solid particles, V_s is the volume of solid particles and V_T is the total volume. Moisture content, w, and saturation, s, are given as follows:

$$W = \frac{M_w}{M_s} \quad (5)$$

$$S = \frac{V_w}{V_v} \quad (6)$$

Where M_w is the mass of water, V_w is the volume of water and V_v is the volume of void spaces. The above equations yield the following expression for saturation, in which W is the density of water:

$$S = \frac{P_d W}{P_w\left(1 - \frac{p_d}{P_s}\right)} = 100\% \quad \text{.............................} \quad (7)$$

The thermal conductivity of a soil increases in 3 stages as the saturation level increases. The gaps between the soil particles are not filled rapidly and thus there is a slow increase in thermal conductivity. When the particles are fully coated with moisture, a further increase in the moisture content fills the voids between particles. This increases the heat flow between particles, resulting in rapid increase in thermal conductivity. Finally, when all the voids are filled, further increasing the moisture content no longer increases the heat flow, and the thermal conductivity does not appreciably increase. The model used to describe this behavior is as follows:

$$S = \lambda_1\left[\sinh(\lambda_2 K + \lambda_3) - \sinh(\lambda_4)\right] \quad (8)$$

Where *S* is the saturation, K is the soil thermal conductivity (w/m^{0}c)

At saturation of zero, the equation reduces to the following:

$$\lambda_2 K_0 + \lambda_3 = \lambda_4 \quad (9)$$

Equation (9) shows that the coefficient λ_4 is related to the thermal conductivity of dry soil, K_0.

Theoretical Consideration of Thermal Conductivity

Several investigations have shown that seed germinating, plant growth and crop yield are influenced by soil temperatures. Chemical reactions and biological decomposition which are at near standstill in cold soils also increase with temperature [7-8]. It shows that a change in soil physical characteristics such as thermal conductivity, specific heat capacity etc. Significantly influence soil temperatures. Consequently, such physical properties are required for predicting soil temperatures of a location [8].

The temperature of a soil at any depth depends on the net amount of heat absorbed by the soil (a factor of thermal productivity), the heat energy required to bring about a given change in temperature of the soil (thermal capacity), and the energy required changes, such as evaporation which occurs constantly at the surface. Thermal conductivity of granular soil depends on the compactness of the soil components and the extent to which water has displaced air in the pore spaces. It increases with increase in both the particle size and the bulk density of the soil. The presence of water films at the points of contact of particles improves the thermal conductivity [7].

Knowledge of thermal properties of soil samples is very important in the choice of the type of soil to be used in the design of a passively cooled building and planting [9]. Heat flow through any soil sample depends on the thermal properties of the soil. Variations in temperature with thickness of the soil determine whether the soil can be used as heat source or sink [10]. These variations in temperature with thickness are determined by the amount of radiant energy that reaches the soil surface, thermal properties of soil, and colour of the soil. The colour determines the proportion of the radiant energy absorbed or reflected by the soil.

Heat flow through the soil = heat transferred from atmosphere to soil + absorbed solar radiation - Re-emitted solar radiation [10]. Using Fourier's equation of heat conductivity, this may translate into the form;

$$K\left({}^{\delta_T}/_{\delta_Z}\right)_{Z=0} = h(T_{atm} - T_{z=0}) + \alpha I - EDR \qquad (10)$$

Where K is thermal conductivity of the soil, h is heat transfer coefficients at the surface, T_{atm} is atmospheric air temperature, T_z is soil surface temperature, Z is soil depth, α is solar radiation absorptivity of the surface, I is intensity of solar radiation, E is long-wave emissivity of the surface, DR is difference between the incident long wave radiation and the radiation emitted from the surface.

Moustafa, *et al*., (1981) [20] provided a general solution to the one dimensional heat conduction equation thus,

$$T(z,t) = Tm\sum_{n=1}^{\alpha} An.\exp(1(nwi + \beta\pi z)) \qquad (11)$$

The equation is modified into the following convenient form [9].

$$T(z,t) = Tm - \text{As} \exp(\beta z) \cos[W(t - t0 - \beta z)] \qquad (12)$$

Where Tm is mean annual ground temperature, ^{0}C; A_S is annual temperature amplitude at soil, T is thermal absorptivity m^{-1}, tis time of the year in days, t_0 is the days of minimum surface temperature, W is angular velocity per day (365 days cycle).

Methodology

Soil samples were collected from three different locations in Akwa Ibom State (Uyo, Itu and Ibiono Ibom). Two different types of soil; clay soils and loamy soils were taken at intervals of 0-20 cm and 0-80 cm respectively from each of the three locations. The samples were crushed with the use of piston and mutter. The crucibles were weighed using a weighing balance and the six different samples were put into the crucibles and reweighed. The samples were then left to dry in the oven for 3 hrs at a control temperature of 100^{0}C. The sample's volumes were recorded before and after drying alongside weighing the dry samples. 50 ml beaker was used for the saturation process of each of the samples with a depth of 1.8 cm for loamy and 1.9 cm for clay. 50 ml of water was added in each beaker, with the dry samples and left for 1 hour. The wet samples were weighed and recorded. The volumes for each sample were also recorded for calculation.

The lee's disc apparatus was suspended with three prices of non-conducting strings attached to retort stand, and clamps. It was carefully placed such that the circular surface of the lower slab was parallel to the horizontal. The dry soil sample was placed on the horizontal surface with the help of a non-conducting cylindrical shaped thin paper measuring about 6.20cm in diameter and 1.40cm in height. The upper slab of the lees disc apparatus was placed such that the dry sand sample was sandwiched between the two slabs. Two thermometers 10-110^{0}C range, were inserted into the gaps provided for thermometers in the lower slab as well as the upper slab. The upper slab was then connected to the steam can or chest with water inside the steam can.

Heat was applied directly to the steam can and allowed to heat until the temperature of the upper and lower slabs started rising up to a level where there seems to be no increment in the temperature recorded by the thermometers any longer. The thermometers were exchanged and the temperature monitored or observed, until the steady state was observed. The steady state temperature before the exchange of thermometers was recorded as T_1 and T_2 for the upper and lower temperatures respectively. The recording was repeated for the sample considering the steady state readings of the exchanged thermometers.

The mean upper temperature was taken and the mean lower temperature was also recorded for that sample. The upper slab was then removed and used to heat up the lower slab at about 10^0c above the mean lower steady state temperature. It was observed with the sample until the temperature become steady and the cooling rate was timed till it got to about 10^0c below the mean lower steady state temperature. The data was used to plot cooling curve and derivation of the gradient for the calculation of thermal conductivity value of the of the soil sample. Same procedure was repeated for all other soil samples.

Results and Discussion

Table 1 presents results of moisture content for the samples determined by routine laboratory soil test. Table 2 presents results of saturation and thermal conductivity for the three samples locations. Table 3 presents the relationship between saturation and thermal conductivity, while table 4 shows the effect of saturation on thermal conductivity. For the individual effect, result revealed that saturation has positive but insignificant effect on thermal conductivity ($\beta = 43.10,$ p>0.05).

According to Johansen (1975), the effect of porosity on thermal properties was more pronounced at higher soil water contents than at lower water contents [11]. However, at soil water contents above the residual water content, the difference in thermal conductivity as a function of porosity at given water content was very consistent. At full saturation, soil has only two phases; water and soil grains. Therefore, a geometric mean equation based on the thermal conductivity of water W/mK at 20 °C) and effective thermal conductivity of soil solids can be used to estimate the saturated thermal conductivity.

Table 1: Moisture content for the three sample sites

Location and Soil type	Uyo		Itu		Ibiono	
	Loamy	**Clay**	**Loamy**	**Cay**	**Loamy**	**Clay**
Sample No.	1	2	1	2	1	2
Weight of tin alone (g)	60.10	60.10	60.20	60.20	74.00	74.00
Weight of tin t sample (g)	92.50	105.30	92.00	96.90	112.60	115.90
Weight of sample alone (g)	32.40	45.20	31.80	36.70	38.60	34.50
Weight of dry soil (g)	89.40	102.10	88.60	95.00	105.40	107.50
Moisture content (%)	57.00	56.90	56.80	58.30	66.80	73.00
Average moisture content (%)	56.95		57.55		69.90	

Table 2: Saturation and thermal conductivity for the three locations

Sample location	Name of sample	Depth (cm)	Saturation	Thermal conductivity
Uyo	loamy soil	0-20	0.10	50.16
	clayed soil	0-80	0.11	50.20
Itu	loamy soil	0-20	0.10	51.72
	clayed soil	0-20	0.10	50.29
Ibiono	loamy soil	0-20	0.12	51.57
	clayed soil	0-80	0.12	51.04

Table 3: Relationship between saturation and thermal conductivity

	Saturation	Thermal conductivity
Saturation	1	
Thermal conductivity	0.225 (0.668)	1

Values in parentheses are the p-values

Table 4: Effect of saturation on thermal conductivity

	β	Standard Error	tcalc.	P-value
Constant (intercept)	56.704	8.90	6.37	0.008
Saturation	43.110	47.94	0.90	0.435^{NS}

NS = not significant at $p<0.05$

Conclusion

The thermal conductivity of soil samples from three locations (Uyo, Itu and Ibiono) has been determined using Lee's steady state method, and the saturation was equally determined. The thermal conductivity values determined shows $50.61 Wm^{-1}k^{-1}$ as the lowest being the thermal conductivity of loamy sample from Uyo while loamy sample collected from Ibiono exhibits the highest thermal conductivity value of $51.565 Wm^{-1}k^{-1}$ followed by loamy sample collected in Itu with thermal conductivity value of $51.72 Wm^{-1}k^{-1}$. The thermal conductivity of clay soil ranges from $50.20 Wm^{-1}k^{-1}$ to $51.04 Wm^{-1}k^{-1}$.

Recommendation

Since saturation has no significant effect on soil thermal conductivity of the soil samples in the study areas (*i.e.* Itu, Uyo and Ibiono), the area can be recommended to farmers for cultivation of crops. Further research into thermal conductivity of soil and the saturation and dry density for the remaining local government areas of Akwa Ibom State should be carried out with a view to finding the correlation between the variables.

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