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Variation of Thermophysical Properties with Porosity in Unconsolidated Materials Using A Transient Method Approach

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Abstract

This study investigated the variation of thermal conductivity and thermal diffusivity of unconsolidated quartz with porosity. The transient method, which involves the application of constant heat flux to a surface of a rectangular container, made of an insulator at the outer edges and covered on the side surfaces by thin sheets of aluminium, containing the samples was employed in determining the thermal conductivity. Results indicate a decrease in thermal conductivity and diffusivity as porosity increased.

Introduction

The earth's heat is one of the principal factors, which influences all geological processes. This is the reason why the thermal properties of soils are important requirements in many fields such as soil science, agronomy and engineering. Processes like seed germination and seedling emergence are influenced by the soil's microclimate, which is in turn influenced by the soil's thermal properties (Ghuman and Lal, 1985). The heat flow in soil may be determined from knowledge of the thermal conductivity and temperature gradient (Noborio and McInnes, 1993).

Calculations of heat dissipation from underground nuclear explosions depend directly on the thermal conductivity values of the earth materials in the explosion regions. The determination of the current-carrying capacity of buried cables as well as the heat losses from underground steam and hot water pipes also requires the values of the thermal conductivities of the soils in which the cables and pipes are laid (Woodside and Messmer, 1961). The factors on which the thermal conductivity of a soil depends can be categorized into two broad groups: those that are inherent to the soil itself e.g. the texture and mineralogical composition and those that can be controlled to a certain degree by human management e.g application of fertilizers, pesticides and presence of industrial pollutants (Yadav and Saxena, 1973).

The attention received by the effect of soil water content on thermal conductivity has been more than that received by the effects of other physical properties of soils (Kunii and Smith, 1960; Al Nakshabandi and Kohnnke 1965; Fritton et al., 1974; Riha et al., 1980). It was found that the thermal conductivity of fluid-saturated, unconsolidated sands decreased with porosity (Woodside and Messmer, 1961). The two classes of most commonly used methods for measuring thermal conductivity namely: one-dimensional (linear) steady state method and two-dimensional (cylindrical) transient method may, in principle,

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give absolute values or relative values compared to some standard. In practice however, the steady state method is mostly used in the comparative mode while the transient method is used in the absolute mode. The steady state methods also require a relatively long time to attain thermal equilibrium and also complicated guarding systems to prevent heat losses.

Unlike steady state methods, transient methods are fast and are said to provide more rapid determinations within a very short period of time than any other method. Transient methods can also be used for a simultaneous determination of thermal conductivity and diffusivity while steady state methods such as the divided-bar technique can be used to determine only the thermal conductivity. For these reasons, the transient method is becoming more popular in the acquisition of data on the thermal properties of soils.

This work investigated the thermal conductivity and diffusivity of unconsolidated quartz obtained from a source within the University of Ibadan campus and also how these two properties are affected by variation in porosity of the samples. This information helps in determining the heat flow through the locations from which the samples were obtained.

Theory

The temperature variation in a one-dimensional homogeneous medium, is governed by the Fourier's heat conduction equation.

The solution of (1) for a given system depends on the initial and boundary conditions suitable for the system. For a system where there is a constant heat flux F into a region $0<x<a$, at zero initial temperature at $x=a$ there was no heat flow over $x=0$, the solution to (1) is

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \qquad (1)$$

$$T(x,t) = \frac{Ft}{\rho ca} + \frac{Fa}{K}\left\{\frac{3x^2 - a^2}{6a^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp(-\alpha n^2\pi^2 t/a^2)\frac{\cos n\pi x}{a}\right\} \qquad (2)$$

$$\therefore T(x,t) = \frac{F\alpha t}{aK} + \frac{Fa}{K}\left\{\frac{3x^2 - a^2}{6a^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp(-\alpha n^2\pi^2 t/a^2)\frac{\cos n\pi x}{a}\right\} \qquad (3)$$

At $x=0$ i.e at the base of the sample

$$T(0,t) = \frac{F\alpha t}{aK} - \frac{Fa}{6K} + Transient\ terms \qquad (4)$$

Where K is the thermal conductivity; α is the thermal diffusivity and a is the thickness of the container (Middleton, 1993). For terms that are large relative to $\alpha\pi^2/a^2$, the transient terms are negligible and the equation relating temperature and time becomes linear. The intercept time t_i on the $T=0$ axis is

$$t_i = \frac{a^2}{6\alpha} \qquad (5)$$

Using equation (5), the thermal diffusivity can be found directly from a series of temperature versus time measurements. The thermal conductivity can be obtained from the relation $K = \alpha\rho c$

where ρ is the density (2650 Kg/m3), c is the specific heat capacity (837.2 J/KgK)

Materials and Methods

The soil sample, which was collected from the stream that flows through the Faculty of Agriculture farm, University of Ibadan, was rinsed and dried after separating the organic matter. The pebbles, and other assorted materials were also removed. By using four different standard sieves, four samples designated as A, B, C and D were obtained.

Thermal conductivity and Diffusivity

The four containers into which the samples were poured were made of an insulator. Each container had internal dimension 4cm x 4cm x 1cm and the two side surfaces of dimensions 4cm x 4cm were covered with thin aluminum sheets. Each aluminum sheet was cut so that its edges do not extend beyond the edges of the insulator. Each sample was poured into a container through the opening at the top and sealed with a strip of the insulator after ensuring that the container was fully packed with the sample.

The container holding the test sample was placed on an aluminum foil in a bigger insulating container, which had been filled close to its mid-point with glasswool. The smaller container was placed in such a way that one of the surfaces covered with aluminum sheet was in contact with the aluminum foil while the other was exposed to the heat source. The foil improves the thermal contact between the surface and the thermocouple probe which was inserted through a tiny hole drilled from beneath. The heat source was placed at about 1cm above the exposed surface of the smaller container in order to create an “oven effect” (Carslaw and Jaeger, 1959), thus eliminating the problems of thermal contact resistance at the surface. The thermal conductivity and thermal diffusivity were determined from the temperatures recorded on the lower surface of the container, at intervals of 30 seconds, when a constant heat flux was applied to the upper surface. Measurement of temperature was done at the following three different points across the length of the container:

1. close to a corner along a diagonal axis
2. at the crossing point of diagonals
3. close to the other corner along the diagonal axis at opposite side.

This was done in order to make provision for the differences in compaction across the length of the container. The standard volumetric method of the ratio of void to the total volume was employed in determining the porosities, Φ of the test samples.

Results and Discussion

The recorded temperatures were obtained after subtracting the ambient temperature (305^{0}k) from the measured temperature values at 30 second intervals. (Table 4). For each sample say, *A*, three curves were obtained for each set of reading and

Table 1: Values of thermal diffusivity α and thermal conductivity *K*, obtained from temperature-time graph from the appendix.

Sample	a(x 10^{-7}m^2/s)			*K*(x 10^{-1}W/mK)		
	1	2	3	1	2	3
A	1.349	1.774	1.349	2.993	3.936	2.993
B	1.495	1.349	1.502	3.272	2.993	3.332
C	1.343	1.299	1.284	2.980	2.882	2.849
D	1.215	1.340	1.331	2.696	2.973	2.953

Table 2: The values of porosity and grain sizes for test samples

Sample	Grain size (µm)	Porosity (%)						
		1	2	3	4	5	mean	Std
A	425	0.395	0.395	0.395	0.395	0.394	0.395	0.001
B	150	0.474	0.474	0.474	0.395	0.395	0.442	0.043
C	65	0.474	0.474	0.474	0.473	0.473	0.474	0.001
D	212	0.474	0.474	0.474	0.526	0.526	0.495	0.028

Table 3: Summary of the average values of physical parameters

Sample	Porosity, Φ (%)	*K(W/mk)*	a(x 10^{-7} m ^{2}/s
A	0.395 ±0.001	3.307 ±0.544	1.491 ±0.245
B	0.442 ±0.043	3.199 ±0.181	1.449 ±0.086
C	0.474 ±0.001	2.904 ±0.068	1.309 ±0.031
D	0.495 ±0.028	2.874 ±0.154	1.295 ±0.070

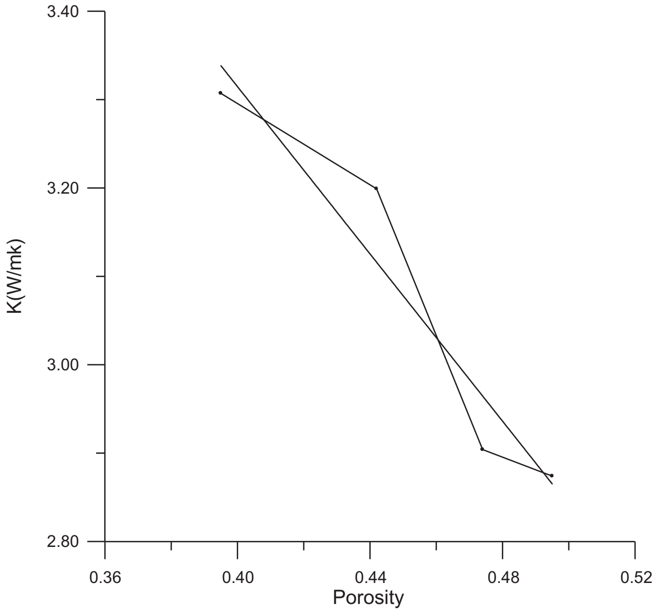

Figure 1: Variation of thermal conductivity with porosity Φ

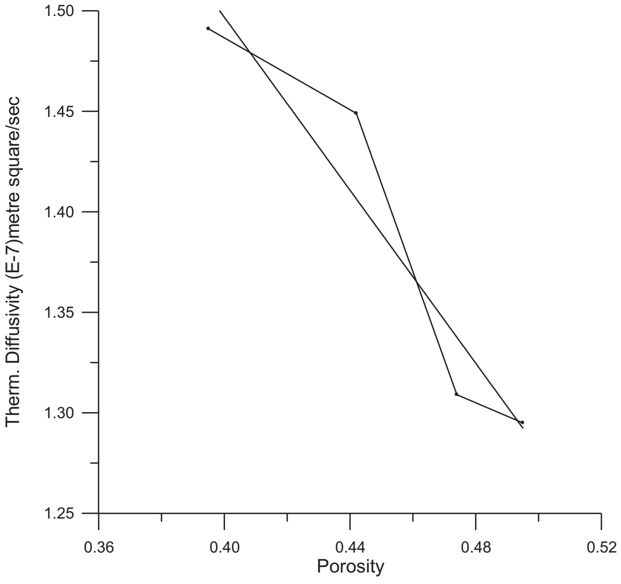

Figure 2: Variation of Thermal diffusivity with porosity

using equations (6) and (7) the values of thermal conductivity and thermal diffusivity were obtained from the temperature-time graphs (Table 1). Table 2 shows the porosity of the samples while Table 3 summarizes the average values for Φ, K, α respectively.

Figures 1 and 2 shows the variation of thermal conductivity and diffusivity with porosity respectively, the results obtained shows that both are inversely related to porosity.

Conclusion

Porous materials are basically comprised of the matrix and air spaces. It is reasonable enough that since the porosity of a material depends on the geometry of the matrix or grains, method of packing or arrangement of the matrix, uniformity of grain size and condition of sedimentation, that when the porosity increases, the percentage void to the matrix ratio increases and air being a bad conductor, it is expected that both thermal diffusivity and thermal conductivity should decrease. However, this is a theoretical assumption which has now been confirmed. Nevertheless, mineral composition must also play a dominant role, in view of this, samples were drawn from the same source with common chemical composition making thermophysical properties to be dependent only on porosity. It should be noted that all the samples considered are from the same source, only that they were separated into grain sizes using standard mesh.

The chemical compounds present in all the samples are the same and this could not have caused the variations in thermal conductivity and diffusivity. The variations are due solely to the variation in porosity. The results obtained showed that thermal conductivity and thermal diffusivity decrease as porosity increases in unconsolidated quartz. Both are linearly related to porosity and are given by equations: $\alpha = -2.1514\Phi + 2.35673$ and $K = -4.731\Phi + 5.2071$ with correlations of 0.90 and 0.92 for thermal diffusivity and thermal conductivity, respectively.

Table 4: Tables showing the values of recorded temperatures at intervals of 30 seconds after the ambient temperature (305^0K) has been subtracted.

Time (sec)		Temp, T of sample A (K)			Temp, T of sample B (K)			Temp, T of sample C (K)			Temp, T of sample D (K)	
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
30	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	1	0	0	0	0	0	0	0	0	0
210	0	0	1	0	0	0	0	0	0	0	0	0
240	1	1	1	1	1	1	1	0	0	0	1	1
270	1	1	2	1	1	1	1	1	1	1	1	1
300	1	1	2	1	1	2	1	1	1	1	1	1
330	1	1	2	1	1	2	1	1	1	1	2	1
360	2	2	3	1	2	2	1	1	1	1	2	2
390	2	2	3	1	2	2	2	1	1	2	2	2
420	2	2	4	2	2	3	2	2	2	2	3	2
450	2	2	4	2	2	3	2	2	2	2	3	2
480	3	3	4	2	3	3	3	2	2	3	3	3
510	3	3	5	2	3	3	3	3	2	3	4	3
540	3	3	5	2	3	4	3	3	3	3	4	3
570	4	4	5	3	4	4	3	3	3	4	4	3
600	4	4	6	3	4	4	4	3	3	4	5	4

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