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Variation of thermal properties in relation to the moisture content in a fine sandy-clay-loam soil at Ile-Ife, Nigeria

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सार – इस शोध पत्र में मई और जुलाई 2001 के मध्य इले – इफ़े नाइजीरिया (7° 33′ उ., 4° 34′ पू.) में उष्णकटिबंधीय स्थल पर 0.10 मी. की गहराई तक धरातल के ऊपरी परत में नमी की मात्रा के साथ मृदा की तापीय विशेषताओं (अच्छी किस्म की बलुई चिकनी मिट्टी/बलुई मिट्टी) में आने वाले परिवर्तनों की जाँच की गई है। 0.05 मी., 0.10 मी., 0.20 मी., 0.30 मी., 0.50 मी. और 1.0 मी. की गहराइयों पर सतही (ऊपरी) तापमान, मृदा जल अंश, भूमंडलीय और शुद्ध विकिरण के साथ–साथ मृदा तापमानों और ऊष्मा फ्लक्स जैसे सूक्ष्म मौसम वैज्ञानिक प्राचल मापे गए।

मिट्टी की ऊपरी परत 0.05–0.10 मी. (अच्छी किस्म की बलुई चिकनी मिट्टी) में 15 और 25% के मध्य तक के मृदा जल अंशों के लिए प्राप्त की गई ऊष्मा क्षमता, तापीय विसरणशीलता, ऊष्मा चालकता और ऊष्मा प्रवेश्यता के औसत मान क्रमशः (0.2 की घट बढ़ के साथ 2.6)$\times 10^{6}$ जे.एम.$^{-3}$ के.$^{-1}$, (0.1 की घट बढ़ के साथ 0.4)$\times 10^{-6}$ एम.^{2} एस.$^{-1}$, 0.3 की घट बढ़ के साथ 1.1 डब्ल्यू. एम.$^{-1}$ के.$^{-1}$, और 0.3 की घट बढ़ के साथ 1.6 जे. एम.$^{-2}$ एस.$^{-1/2}$ के.$^{-1}$ थे। इसी प्रकार मिट्टी की निचली परत 0.10–0.20 एम. (बलुई चिकनी मिट्टी) के लिए प्राप्त किए गए मान क्रमशः (0.1 की घट बढ़ के साथ 0.6)$\times 10^{6}$ जे.एम.$^{-3}$ के.$^{-1}$ (0.2 की घट बढ़ के साथ 0.9)$\times 10^{-6}$ एम.^{2} एस.$^{-1}$, 0.1 की घट बढ़ के साथ 0.5 डब्ल्यू. एम.$^{-1}$ के.$^{-1}$ और 0.2 की घट बढ के साथ 0.6 जे.एम.$^{-2}$ एस.$^{-1/2}$ के.$^{-1}$ थे।

निर्धारित मृदा ऊष्मीय प्राचलों की दैनिक प्रवृत्तियों से परिमाणों का जल अंश के स्तरों के साथ गहरा संबंध पाया गया है। तापीय विसरणशीलता में आयतनी जल अंश की लगभग 20% तक मृदा की नमी की मात्रा के साथ पाई गई किंतु जल अंश में और अधिक वृद्धि होने से इसमें कमी पाई गई। ऊष्मा चालकता और प्रवेश्यता दोनों में मृदा की नमी के स्तरों के समरूपी पैटर्न पाए गए थे।

ABSTRACT. The variation of soil thermal properties (for fine sandy-clay-loam/sandy-clay) with the amount of moisture in the top layer : surface – 0.10 m, has been investigated at a tropical site in Ile-Ife, Nigeria (7° 33′ N, 4° 34′ E) between May and July, 2001. The micrometeorological parameters measured were surface (skin) temperature, soil water content, global and net radiation, as well as soil temperatures and heat flux at : 0.05 m, 0.10 m, 0.20 m, 0.30 m, 0.50 m, and 1.0 m depths.

For soil water contents ranging between 15 and 25% in the top soil layer, 0.05-0.10 m (fine sandy-clay-loam), the mean values of the heat capacity, thermal diffusivity, thermal conductivity, and thermal admittance obtained were : $(2.6 \pm 0.2) \times 10^{6}$ $Jm^{-3}K^{-1}$, $(0.4 \pm 0.1) \times 10^{-6}$ m^2s^{-1}, 1.1 ± 0.3 $Wm^{-1}K^{-1}$, and 1.6 ± 0.3 $Jm^{-2}s^{-1/2}K^{-1}$ respectively. In the bottom layer, 0.10-0.20m (sandy-clay soil), the respective values obtained were: $(0.6 \pm 0.1) \times 10^{6}$ $Jm^{-3}K^{-1}$, $(0.9 \pm 0.2) \times 10^{-6}$ m^2s^{-1}, 0.5 ± 0.1 $Wm^{-1}K^{-1}$ and 0.6 ± 0.2 $Jm^{-2}s^{-1/2}K^{-1}$.

From the diurnal trends of the soil thermal parameters determined, the magnitudes showed strong association with the levels of the water content. The thermal diffusivity was found to increase with the amount of soil moisture, up to about 20% of the volumetric water content, but fell as the water content further increases. Similar patterns of the soil moisture levels were noticeable both for the thermal conductivity and admittance.

Key words – Heat capacity, Thermal diffusivity, Thermal conductivity, Global and net radiation.

1. Introduction

Heat conduction in soils is governed by the thermal properties (*e.g.*, heat capacity), which in turn are strongly dependent on the variation with the water content of the soil (Koorevaar *et al.*, 1983). Water and air are the only soil constituents which vary considerably on a daily basis but since water has about 20 times the thermal conductivity of air it is more influential on the soil thermal properties. Presence of water films at points of contacts between particles not only improves the thermal contact but also replaces air in the soil pore space (Baver *et al*., 1972; Hanks and Ashcroft, 1986).

The soil heat capacity is the amount of heat necessary to raise a unit volume of soil through a temperature change of 1 degree Kelvin. Dry mineral soil has a volumetric heat capacity two to four times that of dry organic material (Stathers and Spittlehouse, 1990). The soil thermal conductivity is a measure of the ability to conduct heat and this property is not a simple constant for a soil type but varies both with depth and time. It is dependent upon the conductivity of soil particles, the soil porosity and the soil water content. In a recent laboratory study of sieved and repacked Jordanian soils (sand, sandy loam, loam and clay loam) by Abu-Hamdeh and Reeder (2000), they found that the thermal conductivity increased considerably with increasing soil density and soil moisture content. From their results they obtained that the thermal conductivity increased from 0.58 to 1.94 for sand, from 0.19 to 1.12 for sandy loam, from 0.29 to 0.76 for loam and from 0.36 to 0.69 $Wm^{-1}k^{-1}$ for clay loam at densities from 1.23 to 1.59 and water contents from 1.4 to 21.2 %. Similarly, Hwang (1995) found that for Kanto loam (Volcanic ash) soil, the soil thermal conductivity decreases as the soil moisture decreases. The thermal diffusivity of the soil controls the speed at which temperature waves move and the depth of thermal influence of the active surface. It is given as ratio of the thermal conductivity to the heat capacity. It may also be viewed as a measure of time required for temperature changes to travel.

Abimbola (2000) investigated the thermal properties for loamy clay/sandy clay soil at a site in the campus of Obafemi Awolowo University, Ile-Ife, based on diurnal variation of soil temperature and heat flux in March 1999. He obtained for the top-soil layer (0.05-0.10m) which was a loamy clay, heat capacity value of 1.499×10^6 J $m^{-3}K^{-1}$, thermal diffusivity of 0.416×10^{-6} m^2s^{-1}. For the bottom layer, 0.10-0.20m, he obtained heat capacity of 0.595×10^6 J $m^{-3}K^{-1}$, thermal diffusivity of 1.330×10^{-6} m^2s^{-1}. In an independent investigation for the same location by Balogun (2000), he showed that the soil thermal properties all varied considerably with the soil moisture content. Since there were no simultaneous measurements of soil moisture carried out, he therefore related the estimated values to two classes: rainy (wet) days and dry days. Adjepong and Afriye (1977) had studied the seasonal variation of thermal diffusivity for axim soil at three different sites in Ghana. They showed that the diffusivity obtained by amplitude and phase methods for the three layers: 0.05-0.10 m, 0.10-0.20 m, and 0.20-0.30 m indicated similar temporal variations. The values they obtained were $(0.6\text{-}2.2) \times 10^{-6}$ m^2s^{-1}, $(0.8\text{-}1.7) \times 10^{-6}$ m^2s^{-1}, and $(1.2\text{-}21.5) \times 10^{-6}$ m^2s^{-1} for these respective layers. The topmost layer, 0.05-0.10 m showed the largest month-to-month fluctuation, which is indicative of the change of soil wetness with the change of seasons (*i.e*., the rainy and dry seasons).

In this study, we have calculated values for the soil thermal properties with varying degrees of wetness for a specific soil type (sandy-clay-loam : 52.46% sand, 22.97% silt and 24.57% clay and sandy-clay : 51.12% sand, 13.64% silt and 35.24% clay) in a tropical location. In none of the previous studies reported for the area (Babatunde, 1980; Ewanlen, 1997; Abimbola, 2000; Balogun, 2000) had there been independent measurements of soil moisture nor detailed characterisation of the soil carried out to determine variation of the soil thermal properties. It is expected that the present contribution will make up for such deficiencies.

2. Methodology

There are a number of ways available to calculate soil thermal properties (heat capacity, thermal conductivity and diffusivity). An experimental approach to determine thermal conductivity, k is to pass a known quantity of heat per second (soil heat flux, H_G) through a soil of known cross-sectional area, A and then measure the temperature of the soil T_1 and T_2 at depths z_1 and z_2. By so doing, we can then solve the following equation :

$$\frac{H_G}{A} = -k\,\frac{(T_2 - T_1)}{(z_2 - z_1)} \tag{1}$$

for k. The thermal diffusivity, D can be estimated using the phase method (Jackson and Kirkham, 1958), from the relationship,

$$D = \frac{P\,(z_2 - z_1)^2}{4\pi\,(t_2 - t_1)^2} \tag{2}$$

where t_1 and t_2 are the times at which the maxima of the temperature waves reach the depths z_1 and z_2 and P is the period of the temperature wave (in this case, 1 day ≡ 86400 secs). Determining D by Eqn. 2 above

TABLE 1

Instruments deployed for the field measurements

Parameter	Device	Height (m)	Accuracy
Wind speed	Cup anemometer	1.44	distance const. = 2.3 m
Wind direction	Wind vane	4.44	+/- 2 deg.
Air temperature	Psychrometer	0.58, 3.58	+/- 0.05° C
Surface temperature	Infrared Pyrometer	1.14	+/- 0.5° C
Soil temperature	PT- 100 ohms	-0.05, -0.10, -0.2, -0.3, -0.5, -1.0	+/- 0.05° C
Air pressure	Capacitive barometer	1.30	1 hPa
Soil heat flux	Heat flux plate	-.05, -0.1, -0.2, (-1.0)	13.5 $\mu V/Wm^{-2}$
Soil moisture	Water content reflectometer	-0.10	+/- 3% of water content
Global radiation	Pyranometer	1.22	23.94 $\mu V/Wm^{-2}$
Net radiation	Net radiometer (REBS)	1.22	+9.6 (-11.9) $\mu V/ Wm^{-2}$

includes errors due to liquid and vapour transport of heat, which may at times be substantial (Kirkham and Powers, 1972). Another approach, where the heat conductivity, k and heat capacity, C are known, the thermal diffusivity can be calculated from, $D = k/C$.

The amount of heat absorbed, ΔH, within the soil is proportional to the time rate of change of temperature, ΔT and the heat capacity, C of the soil. Thus, the soil heat capacity can be determined from the measurement of heat flux and the soil temperature at specified depths.

The dependence over a soil layer of thickness Δz is given by

$$\frac{\Delta H}{\Delta Z} = C\,\frac{\Delta T}{\Delta t} \tag{3}$$

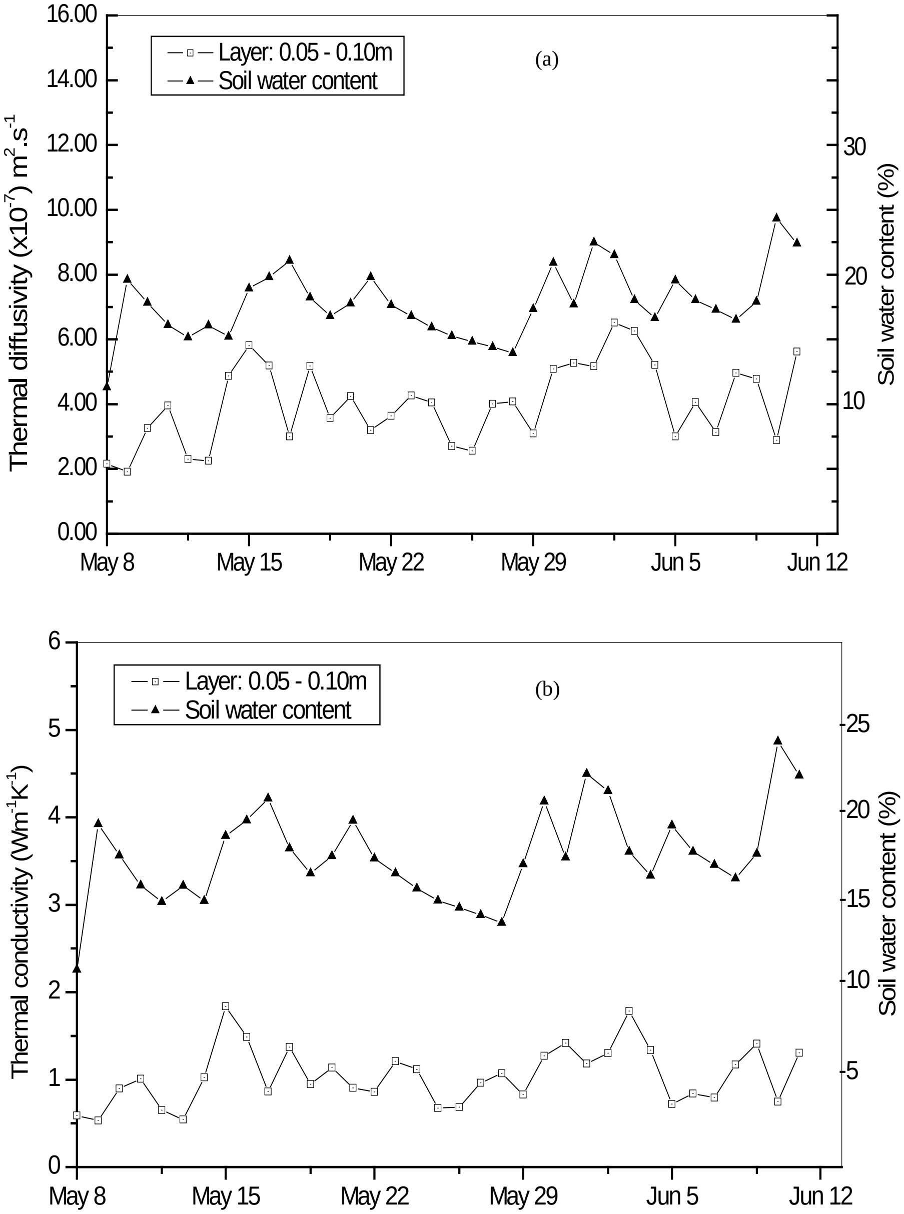
A property which is related to the above mentioned soil thermal characteristics is the thermal admittance, μ_s. The admittance is a measure of the ability of a soil surface to accept or release heat. This soil parameter is given by,

$$\mu_s = Ck^{-1/2} = (DC^{-1})^{-1/2} \tag{4}$$

It is to be noted that the ratio of soil thermal admittance to that of the surrounding air determines the sharing of sensible heat between the soil and the atmosphere. The soil admittance, μ_s increases with the soil moisture content (Oke, 1996).

The location where the project was sited is a disused climatological station located within the campus of Obafemi Awolowo University in Ile-Ife, Nigeria (7° 33′ N, 4° 34′ E). This is within the tropical rain forest zone of West Africa. The location experiences about seven months of rains (Wet season, April – October) which alternates a dry season (November – March). The annual rainfall averages between 1000 and 1500 mm. During the run of the field study, it fell within the rainy season in the area. As such precipitation was almost a daily occurrence.

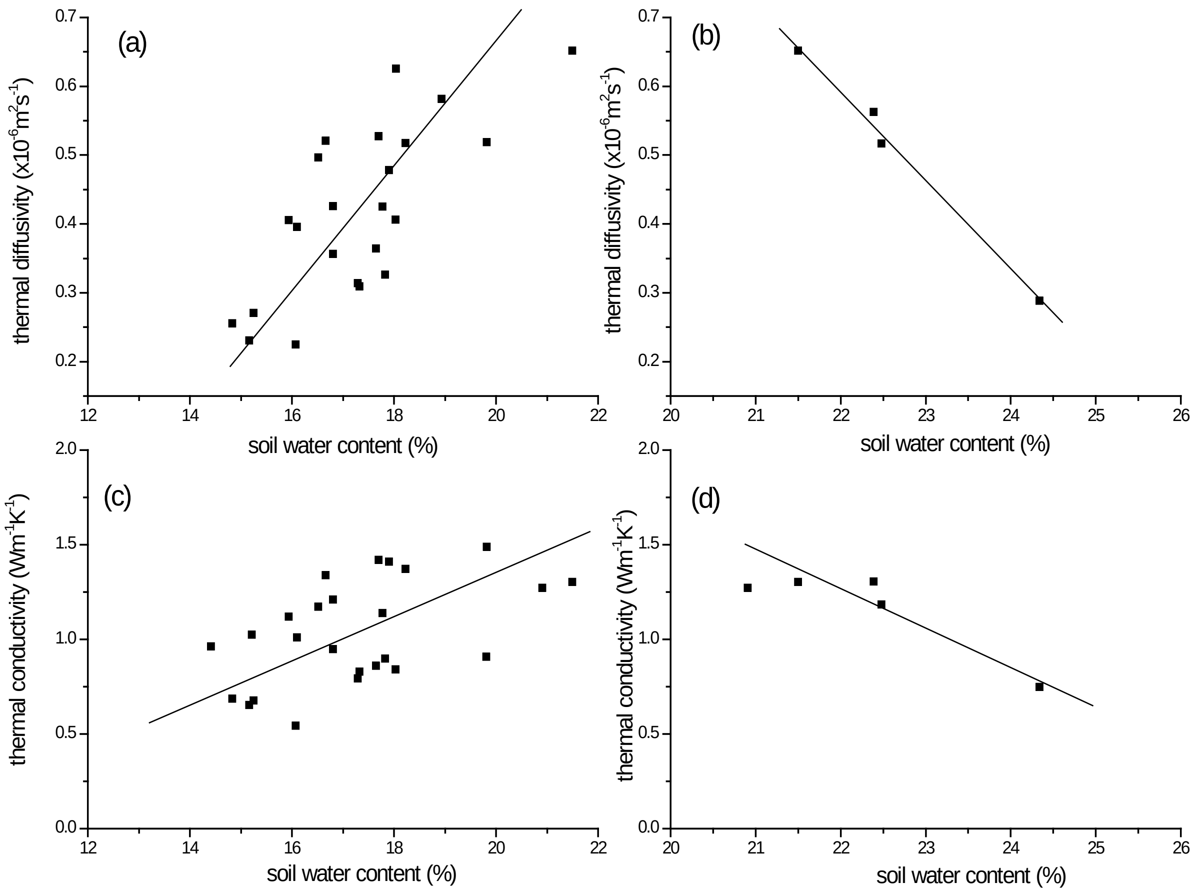
The rectangular-shaped measurement area (approximately 750 square meters) was a flat bare ground. Albedo of the measurement site has been previously estimated by Balogun (2000) and the values obtained ranged between 0.12 and 0.16, depending largely upon the degree of wetness of the surface. A trench of approximately 0.75 × 0.75 m^2 was dug with the soil carefully removed to separate the different soil layers. Buried in the soil at six depths (0.05 m, 0.10 m, 0.20 m,



Figs. 1(a&b). (a) Thermal diffusivity with soil water content in the soil layer : 0.05-0.10 m for the period : May 8th – June 12th, 2001 at the site. (b) same as (a) but for thermal conductivity

0.30 m, 0.50 m and 1 m), were soil temperature probes and soil heat flux plates (0.05 m, 0.10 m and 0.20 m, later moved to 1.0 m), and a soil water content reflectometer (model CS 615 manufactured by Campbell Scientific). These probes were sampled every 10 seconds and then averaged to produce the 1 minute statistics. A detailed listing of the various devices used and specifications are given in Table 1.

The soil sample at the measurement site was collected using a cylindrical core sampler (Core method) and the bulk density determined to be 1.51×10^3 kg m^{-3}. With the use of a soil triangle chart, the percentage compositions were obtained as follows : (*i*) for the top layer, 0 – 0.05 m, the sand is 52.46%, silt is 22.97% and clay is 24.57%; for the middle layer, 0.05-0.10 m, sand is 51.79%, silt is 14.97% and clay is 33.24%, and for the

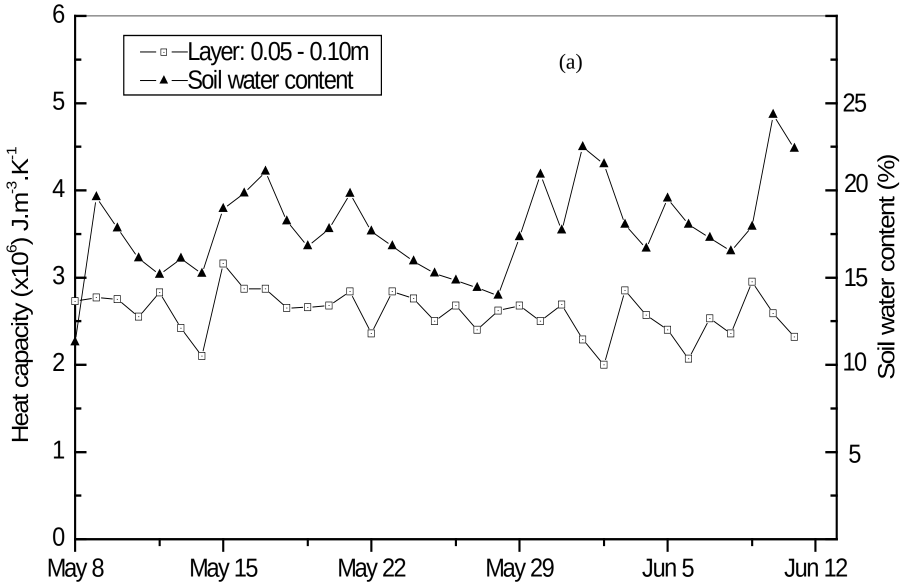


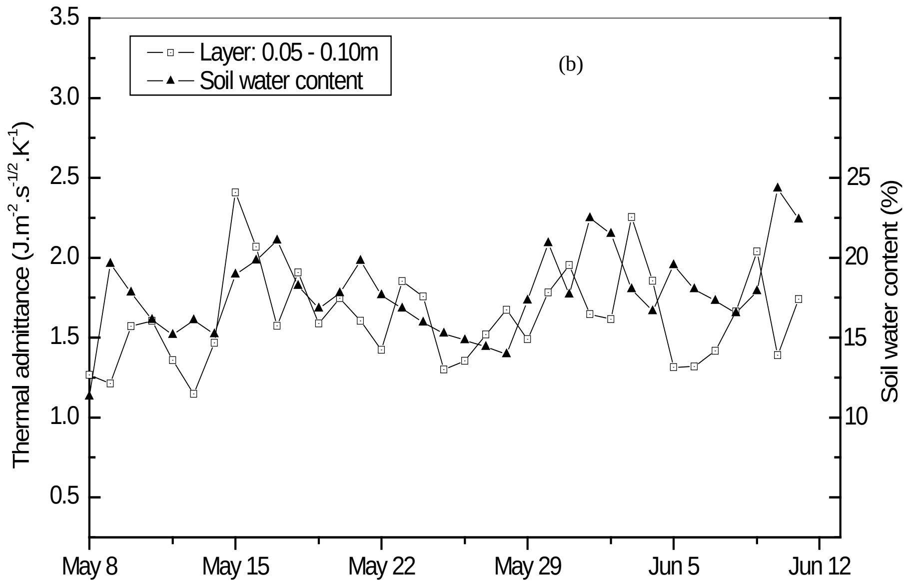
Figs. 2(a-d). Scatter plots of thermal diffusivity with (a) < 20% water content and (b) >20% water content. Thermal conductivity with (c) < 20% water content and (d) >20% water content

bottom layer, 0.10-0.20 m, sand is 51.12%, silt is 13.64% and clay is 35.24%. The first two layers, are characterized as fine sandy-clay-loam soil while the third layer (0.10-0.20 m) is of the sandy-clay type. The field experiment took place between 8th May to 12th July, 2001. It was during a raining season with relatively few days of dryness.

3. Discussion of results

The variation of the following thermal properties : (*i*) thermal diffusivity, (*ii*) heat capacity, (*iii*) thermal conductivity and (*iv*) thermal admittance, with the soil water content (in the top layer, 0.05 – 0.10 m, fine sandy-clay-loam : 51.79% sand, 14.97% silt and 33.24% clay) are discussed on a day-to-day basis during the special observation period, 8th May – 12th June, 2001. In Fig. 1(a), the thermal diffusivity increases with the soil water content as portrayed by the trend on the following days : 14th to 16th of May. From the weather summary, it rained on the 13th and 15th and on the subsequent days, it was mostly cloudy with the soil conditions increasingly damp (from about 15% volumetric soil water content on the 14th to approximately 20% on the 16th). Correspondingly, the thermal diffusivity increased from about 0.45×10^{-6} m^{2}s^{-1} to 0.60×10^{-6} m^{2}s^{-1}. From the 21st to 28th of May, it was fairly dry and sunny period. This is noticeable in the values of soil water content recorded which gradually dropped from about 20% on the 21st, to about 13% on the 28th. During this relatively dry period, the diffusivity value was low and fluctuated around $(0.36 \pm 0.07) \times 10^{-6}$ m^{2}s^{-1}. From the 29th when the rainfall activity resumed, the soil water content rose up accordingly and the thermal diffusivity shot upwards in values as well (peaking to about 0.65×10^{-6} m^{2}s^{-1} on the 2nd of June). Noticeable for

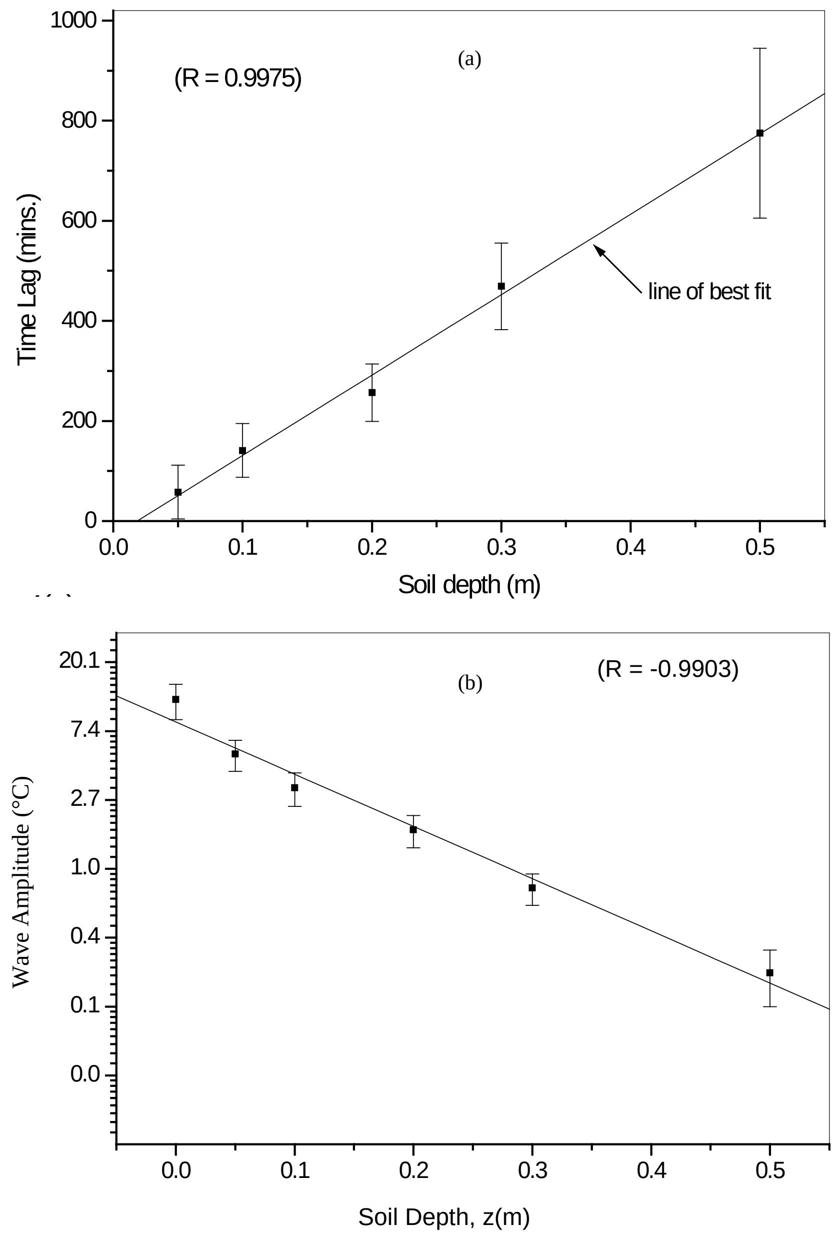




Figs. 3 (a&b). (a) Heat capacity with the soil water content in the soil layer : 0.05-0.10 m for the period : May 8th – June 12th, 2001 at the site. (b) same as (a) but for thermal admittance

the 10th of June is that when the soil water content increased to about 25%, the thermal diffusivity value fell to 0.29×10^{-6} m^{2}s^{-1}. This is understandable because the thermal diffusivity increases with the soil moisture until it reaches a maximum value at about 20 per cent by volume of water content and beyond, it falls (Oke, 1996).

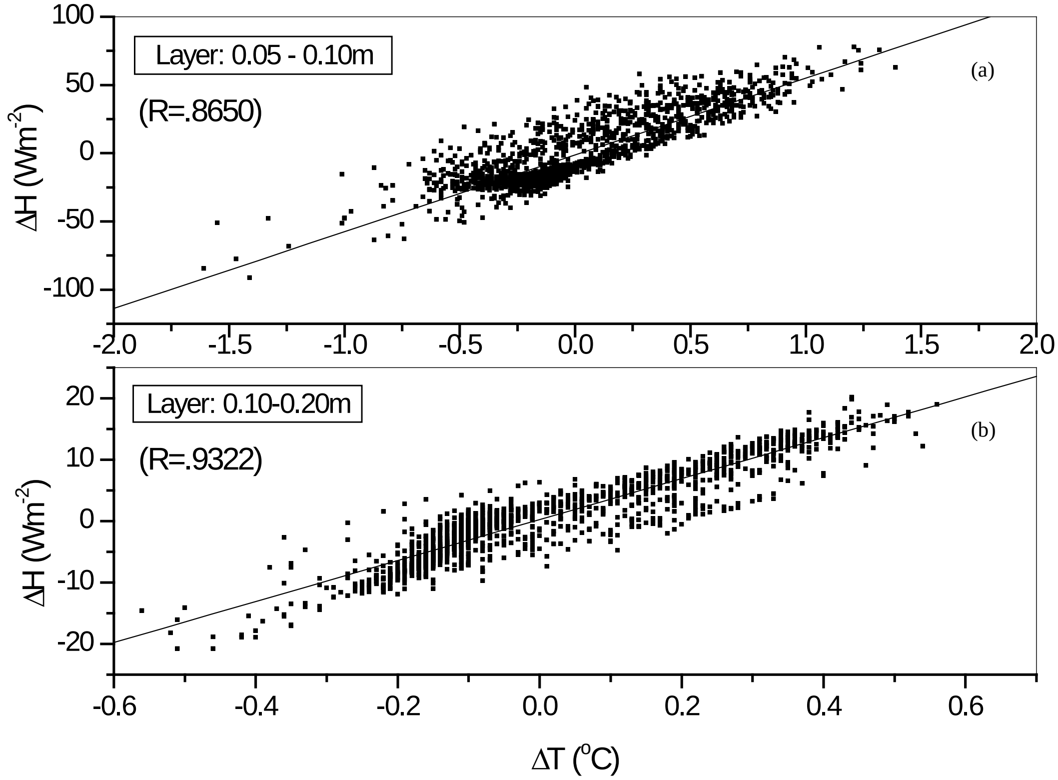
Fig. 1(b) shows the variation of the soil thermal conductivity together with the soil water content during the same study period. It can be observed from this figure that the soil conductivity is fairly constant and varies weakly (standard deviation, S.D. = 0.3 Wm^{-1}K^{-1}) with the soil moisture content. Between the 21st and 28th of May, the volumetric soil water content dropped from 20% to 13%, while the conductivity initially increased from 0.8 Wm^{-1}K^{-1} to 1.4 Wm^{-1} K^{-1} and later dropped to about 0.6 Wm^{-1}K^{-1} (for fine sandy-clay-loam). Further, the thermal conductivity rose in values as the water content increased



Figs. 4(a&b). (a) Plot of the time lag against the soil depth at the site. (b) same as (a) but for wave amplitude

when it rained again on the 29th. We have also noticed that there is a limiting value (peak) to the thermal conductivity at about 20% of soil water content beyond which the conductivity falls in values (Oke, 1996). For instance, on the 10th of June when the soil water content was approximately 25%, the corresponding value of conductivity dropped to about 0.5 $Wm^{-1}K^{-1}$. Thus both the thermal diffusivity and conductivity showed a similar variation with the soil moisture content [Figs. 2(a-d)].

Fig. 3(a) shows the variation of the heat capacity and soil water content for the same period. The heat capacity is observed to be positively correlated with the degree of soil wetness. For instance, between the 14th and 15th of May, the soil water content increased from about 17% to 22% by volume and correspondingly, the heat capacity value estimated rose sharply from 2.0×10^{-6} J m^{-3} K^{-1} to 3.3×10^{-6} J m^{-3} K^{-1} (for fine sandy-clay-loam : 52.46% sand, 22.97% silt and 24.57% clay). Also, from this same



Figs. 5(a&b). Plot of the heat storage, ΔH against the temperature gradient ΔT for the soil layers : (a) 0.05-0.10 m (fine sandy-clay-loam) and (b) 0.10-0.20 m (sandy-clay)

figure, between 22nd and 23rd of May, when the soil water content reduced from about 21% to 17.5%, the value of the heat capacity reduced from 2.8×10^{-6} J m^{-3} K^{-1} to 2.1×10^{-6} J m^{-3} K^{-1}. Thus establishing a linear relationship between the soil heat capacity and the soil water content. The present results compare well with the values in published literature (Jury *et al*., 1991).

Fig. 3(b) shows the variation of the thermal admittance with the soil water content. The thermal admittance varied significantly with the soil moisture content. On the 14th and 15th of May, the soil water content were 17% and 22% respectively and the values obtained for the thermal admittance increased from 1.5 Jm^{-2}s$^{-1/2}$ K^{-1} to 2.2 Jm^{-2}s$^{-1/2}$ K^{-1} (for fine sandy-clay-loam: 51.79% sand, 14.97% silt and 33.24% clay) respectively. Further increase in the soil wetness to 24% on the 16th of May caused the thermal admittance to drop to approximately 1.2 Jm^{-2}s$^{-1/2}$ K^{-1}. Thus, to a certain level of soil wetness (about 21%), the thermal admittance increases with the wetness, but with further increase in soil wetness this quantity reduces.

From the plot of the time lag between two successive crests of the thermal wave and the soil depth (phase method), the soil temperature data over the whole period of field observation (*i.e.*, May 8th – June 12th) showed a linear variation as in Fig. 4(a). The slope of the graph yielded the damping depth, $d_s = 0.159$ m. From this value, we determined for the layer averaged soil thermal diffusivity, $D = 0.92 \times 10^{-6}$ m^{2}s^{-1}. Similarly in Fig. 4(b), the logarithm of the wave amplitude is shown to vary linearly with the soil depth. The second graph gave a value of the damping depth, $d_s = 0.132$ m. Using this value, the thermal diffusivity, $D = 0.63 \times 10^{-6}$ m^{2}s^{-1}. The difference between the two values is attributable to the fact that due to the presence of higher harmonics in the diurnal thermal wave the time lag method tends to overestimate (Cannuffo and Bernadi, 1982).

To obtain heat capacity from the soil heat flux and temperature measurements, the two graphs in Figs. 5(a&b) show scatter plots of the heat flux gradient ΔH, and the temperature gradient ΔT, for the two soil layers: (*i*) 0.05-0.10 m. (fine sandy-clay-loam: 51.79% sand, 14.97% silt and 33.24% clay) and (*ii*) 0.10-0.20 m (sandy-clay : 51.12% sand, 13.64% silt and 35.24% clay). The correlation coefficients obtained for the two layers were 0.8650 and 0.9322 respectively, from the lines of best fit. From the slopes of the graphs in Figs. 5(a&b) the heat capacities calculated were 2.03×10^6 $Jm^{-3}K^{-1}$ and 0.60×10^6 $Jm^{-3}K^{-1}$ for the two layers, 0.05-0.10 m and 0.10-0.20 m respectively. The values of the heat capacity thus obtained above indicate the different soil types in the layers and from the tables (Oke, 1996), for clay soil with 40% pore space of varying degree of wetness, typical values of heat capacity ranges from 1.42 to 3.10 ($\times 10^6$ $Jm^{-3}K^{-1}$).

4. Conclusions

Values of the soil thermal properties (thermal diffusivity, heat capacity, thermal conductivity and thermal admittance) obtained have shown a strong association with the degree of soil wetness for the fine sandy-clay-loam. Mostly, there is a positive linear correlation with the volumetric water content for all the parameters. However, we have found that there is a ceiling value of about 20% soil water content beyond which the thermal diffusivity falls in magnitude. Similar trend is obtained for thermal conductivity and thermal admittance. The behaviour agrees well to that in literature (van Wijk and de Veries, 1966).

For the top soil layer, 0.05-0.10 m (fine sandy-clay-loam), the mean values of the heat capacity, thermal diffusivity, thermal conductivity and thermal admittance determined were: $(2.6 \pm 0.2) \times 10^6$ $Jm^{-3}K^{-1}$, $(0.4 \pm 0.1) \times 10^{-6}$ m^2s^{-1}, 1.1 ± 0.3 $Wm^{-1}K^{-1}$, and 1.6 ± 0.3 $Jm^{-2}s^{-1/2}K^{-1}$ respectively. For the bottom layer, 0.10-0.20m (sandy-clay soil), the respective values obtained were: $(0.6 \pm 0.1) \times 10^6$ $Jm^{-3}K^{-1}$, $(0.9 \pm 0.2) \times 10^{-6}$ m^2s^{-1}, 0.5 ± 0.1 $Wm^{-1}K^{-1}$ and 0.6 ± 0.2 $Jm^{-2}s^{-1/2}K^{-1}$.

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