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THE THERMAL CHARACTERISTICS OF SOME HIGHLY WEATHERED SOILS OF PENINSULAR MALAYSIA

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Keywords: Conductivity, Diffusivity, Texture, Stability, Moisture, Porosity.

RINGKASAN

Sifat-sifat terma tanah yang utama ditakrif dan dibincangkan.

Bagi tanah-tanah terluluhawa di Semenanjung Malaysia, kandungan pasir mempengaruhi daya pengaliran dan daya peresapan terma. Kandungan pasir yang tinggi menyebabkan peningkatan sifat-sifat terma tersebut. Saiz pasir juga memainkan peranan yang penting dan ini ternyata apabila perbandingan dibuat di antara tanah-tanah dari siri Bungor dan Rengam. Peranan air dalam perubahan sifat-sifat terma tanah juga bergantung kepada kandungan pasir. Kandungan pasir yang tinggi menyebabkan peningkatan daya pengaliran dan daya peresapan terma yang lebih tinggi, terutama apabila kandungan air volumetrik > 0.16.

Pemindahan terma berkurangan bagi tanah-tanah yang mengalami kepecahan agregat akibat terlalu basah. Selain daripada kestabilan agregat, saiz agregat dan keronggaan tanah juga mempengaruhi sifat-sifat terma tanah.

INTRODUCTION

The thermal properties of the soil influence the soil temperature regime and characterize the soil's capacity to absorb, release and transmit heat energy. Some of the more important properties are heat capacity, thermal conductivity, thermal diffusivity and damping depth.

The temperature of a soil depends directly on its heat capacity since the amount of temperature change in response to the absorption or release of heat is influenced by the heat capacity. Fluctuations in soil temperature, which are important factors in plant growth, are strongly influenced by these thermal properties.

These fluctuations are greatest in the surface layer of the soil which receives solar radiation during the day and loses heat to the atmosphere at night. The heat received at the surface is propagated to the lower layers by heat conduction in the form of waves, but with a reduction in amplitude and a progressive increase in time-lag.

However, heat capacity and thermal conductivity vary greatly between soils because different soils are made up of different proportions of sand, silt, clay and organic matter, and are of different structure. In Peninsular Malaysia there are large variations in soil texture and structure. Moreover, being situated in the equatorial zone, with air temperatures of around 30°C during the day, soil temperatures which are in excess of the optimum for the growth of many crops do occur in this country (MAENE, MAESSCHALK, LIM and MOKHTARUDDIN MANAN, 1979; TODOROV, 1980).

Although the principles of heat conduction are universally well-known and soil thermal characteristics can usually be inferred from soil physical properties, up till now no quantitative information on thermal properties is available with respect to Malaysian soils. This paper reports and discusses the thermal characteristics of several soils of different textural and structural properties in an attempt to contribute to the pool of basic soil data, and to provide examples of how temperature

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changes in soils can be varied by differences in their physical properties.

DEFINITIONS

The explanation of symbols is given in *Appendix 1*. Specific heat is the amount of heat in joules required to raise the temperature of 1 kg of soil 1 K, and heat capacity, C is the product of specific heat and the mass of the soil. The volumetric heat capacity, C_v in $J/m^3/K$ of a soil constituent is equal to the product of its specific heat and its density, ρ. The volumetric heat capacity of the whole soil is the sum of the volumetric heat capacities of all the constituents of the soil (JANSE and BOREL, 1965; MONTEITH, 1973). Thus,

$$C_v \text{soil} = \Sigma C_{v_i} X_i \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where i is a soil constituent and X is the volume fraction of a soil constituent.

The specific heat and the volumetric heat capacity may also be referred to as gravimetric specific heat and volumetric specific heat respectively.

The thermal conductivity, λ in J/m/s/K is the amount of heat that flows through a unit area in a unit time under unit temperature gradient. The thermal diffusivity, a in m^2/s is equal to $\frac{\lambda}{C_v}$ and represents the temperature change that takes place in any portion of the soil as heat flows into it from an adjacent layer (JANSE and BOREL, 1965; TAYLOR and JACKSON, 1965).

The damping depth, D is the depth at which the amplitude of the wave of the periodic temperature variations is reduced to e^{-1} or 0.37 times the amplitude at the surface (VAN WIJK and DE VRIES, 1966; MONTEITH, 1973). The relation between D and the other thermal variables is

$$D = (2\lambda / C_v \omega)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where ω is the angular frequency in per second.

For the diurnal temperature variation, ω = 7.27 x 10^{-5}/s and for the annual variation, w = 1.99 x 10^{-7} per second. D gives an idea of the depth to which the soil will be warmed up.

MATERIALS AND METHODS

Soils

Soil samples of < 2 mm in diameter of Bungor, Kuantan, Munchong and Rengam series were used. These soils have large differences in texture *(Table 1)* and are representative of the sedentary soils of Peninsular Malaysia. Other relevant details of the soils are also given in *Table 1*.

In order to investigate the role of aggregate size in the variations of thermal properties of soils, measurements were also made on aggregates of diameter 3−5 mm and 5−8 mm and on mixtures of different-sized aggregates of Munchong series soil.

Theory of Method

In order to minimize the effects of heat transfer by water movement when temperature gradients are introduced to the soil, a transient heat flow technique was used to measure thermal conductivity.

Thermal conductivity was determined from temperature variations in the proximity of a heat source which was a needle in which a heating filament and a thermocouple were built. The reference junction of the thermocouple was placed in a column of sand which was maintained at a constant temperature in a water bath. The needle, or probe, was placed in a column of soil and heated. As the heat spread out radially from the probe, the probe temperature was recorded continuously in relation to time.

The temperature varies according to the heat input, the thermal contact resistance between the probe and the soil

Table 1. Sampling location, classification and some properties of the soils (0–15 cm layer) under study

Soil series	Sampling location	Classification according to soil taxonomy	Particle size distribution (%)				Organic matter content (%)	pH (H_2O)
			<2µm	2–20µm	>20–200µm	>200 µm		
Bungor	Serdang, Selangor	Typic Paleudult	42.1	1.7	33.3	22.9	2.80	4.8
Kuantan	Bukit Goh, Pahang	Haplic Acrorthox	63.5	25.3	6.5	4.7	4.53	4.7
Munchong	Serdang, Selangor	Tropeptic Haplorthox	71.3	6.8	11.4	10.5	2.87	4.5
Rengam	Sg. Buloh, Selangor	Typic Paleudult	49.6	6.1	7.7	36.6	3.68	4.5

and the thermal properties of the probe and the soil. The heat flux is proportional to the temperature and the thermal conductivity,

$$\frac{\delta T}{\delta t} = \frac{\lambda}{C_v}\left\{\frac{\delta^2 T}{\delta r^2} + \frac{1}{r}\frac{\delta T}{\delta r}\right\} \qquad (3)$$

Equation 1 is the one-dimensional form of Fourier's law of heat conduction (DE VRIES, 1966). With the exact initial and boundary conditions, and at times t_1 and t_2, Equation 3 becomes

$$T_2 - T_1 = \frac{Q}{4\pi\lambda} \ln t_2/t_1 \qquad (4)$$

Where T_1 and T_2 are temperatures at t_1 and t_2 respectively, and r is the distance from the centre of the needle.

Calibration of the Thermocouple

The scheme for the calibration of the thermocouple is shown in *Figure 1.* The cold junction of the thermocouple and a thermometer were placed in a cylinder filled with water at room temperature. The needle, containing the hot junction, was placed in thermostatic water bath. The temperature of the bath was increased in steps of 1°C in the range from 14°C (287 K) to 25°C (298 K). At every temperature increase the potential difference between the cold and hot junctions was measured with a recorder.

The calibration curve is shown in *Figure 2.* The slope of the graph of potential difference versus temperature gives the increase in potential per unit temperature (µV/K). In *Figure 2,* the slope is 0.017 microvolt per degree Kelvin.

Measurement of Thermal Conductivity

The soil was moistened to the desired moisture content by adding water dropwise from a burette. While water was being added the soil was stirred vigorously with a spatula to ensure thorough mixing. The moistened soil was packed into a 250-ml measuring cylinder. To ensure a uniform bulk density, the soil was added in small

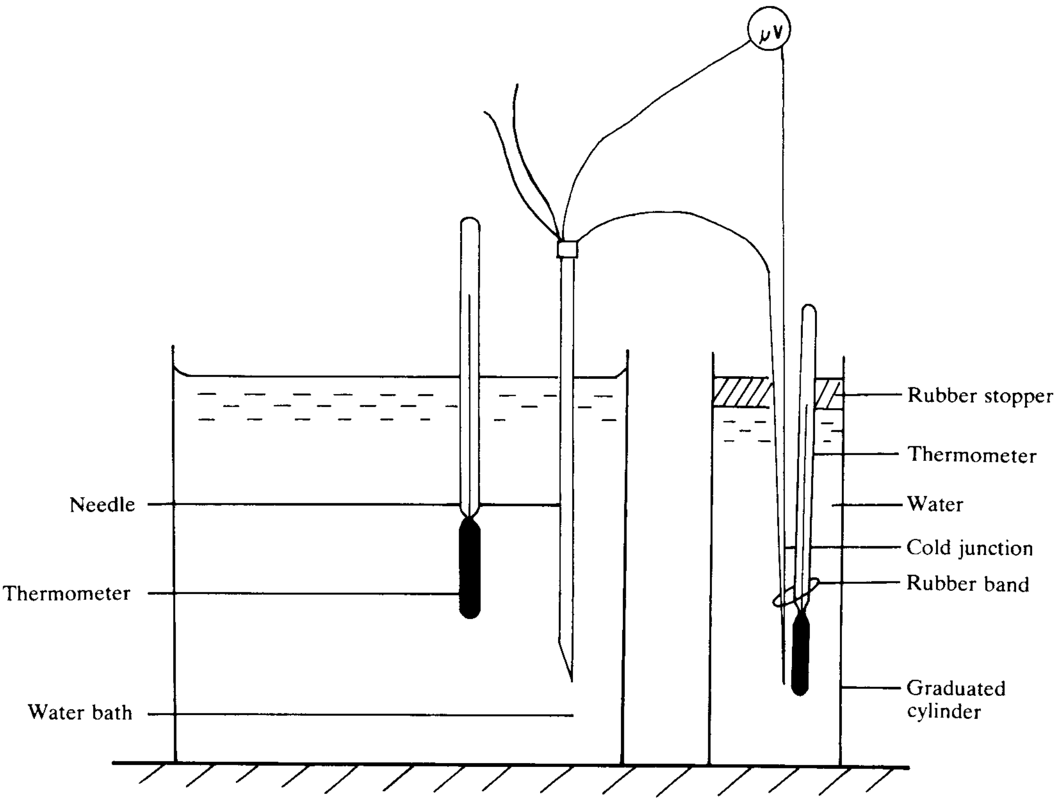

Figure 1. Apparatus for the calibration of a thermocouple.

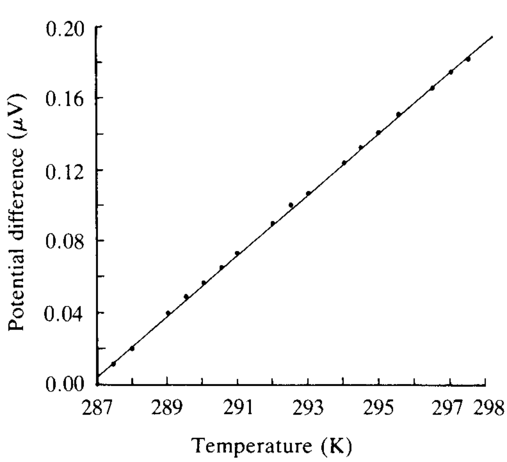

Figure 2. Calibration curve for the thermocouple.

portions, each addition being followed by stamping of the cylinder on a piece of thick cloth placed on a wooden table. Absolute uniformity of packing was not achieved. However, errors were minimized by varying the number of stampings to suit the prevailing conditions for the various samples.

The cylinder was placed in a thermostatic water bath maintained at a temperature of 25° Celsius. The cylinder containing the soil sample, and a cylinder containing sand, in which the cold junction was placed, were allowed to equilibrate in the bath for one hour. The apparatus is shown in *Figure 3*.

When a measurement was made, the needle was placed in the soil sample and the current switched on for 100 seconds. The potential difference between the hot and cold junctions was measured continuously with a recorder.

The slope of the graph of potential difference versus log t (time in seconds) is represented by b_1, whilst the potential

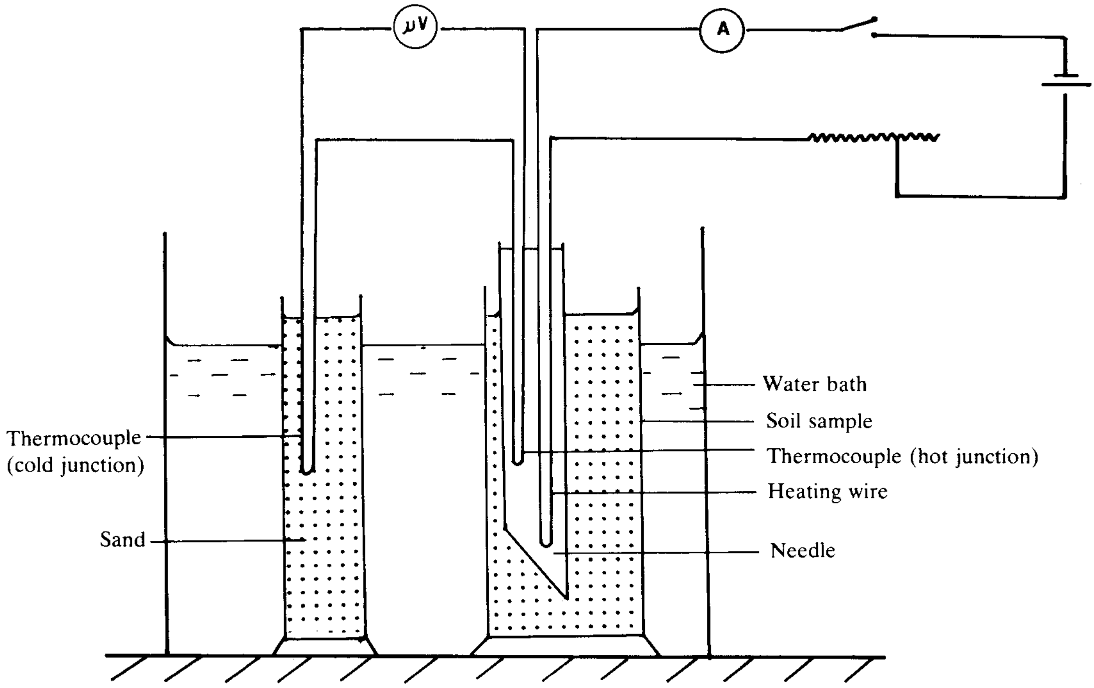

Figure 3. Apparatus for the measurement of thermal conductivity.

difference per unit temperature difference is represented by b_2. The thermal conductivity was calculated using Equation 7 (shown below) which can be derived from Equation 4.

Equation 4 can be rewritten as

$$T_2 - T_1 = \frac{0.37\, I^2 R}{\lambda} \log t_2/t_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\text{But } b_1 = \frac{I^2 R}{\log t_2/t_1} \qquad \text{and } b_2 = \frac{I^2 R}{T_2 - T_1}$$

$$\text{Therefore } \frac{\log t_2/t_1}{T_2 - T_1} = \frac{b_2}{b_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$\text{Therefore } \lambda = 0.37\, I^2 R\, b_2/b_1 \quad \ldots\ldots\ldots\ldots\ldots (7)$$

Calculation of Volumetric Heat Capacity

The values of bulk density, moisture content (w/w) and organic matter content (w/w) were used to calculate the volume fractions of water, mineral matter and organic matter.

The volumetric heat capacity, $C_v = \sum_{i=1}^{n} C_{v_i} X_i$ where X_i is the volume fraction of a soil component. As the major soil components are mineral matter, organic matter and water,

$$C_v = (2\,009\, X_m + 2\,512\, X_o + 4\,186\, X_w)\, 10^3 \text{ J/m}^3\text{/K} \quad \ldots\ldots\ldots (8)$$

where X_m is the volume fraction of mineral matter, X_o is the volume fraction of organic matter and X_w is the volume fraction of water.

RESULTS AND DISCUSSION

A Comparison of the Thermal Properties of Mineral Soils, Pure Sand, Clay and an Organic Soil

Since soils are mixtures of several different materials, the thermal properties of different soils vary considerably, depending on the proportions of the constituent

Table 2. Thermal properties of some soils and soil constituents

Material	Sand content (%) Coarse sand	Sand content (%) Fine sand	Total porosity	Volumetric moisture content	Thermal conductivity (J/m/s/K)	Volumetric heat capacity (10^6J/m^3/K)	Damping depth (m 10^{-2})
Sand*	–	–	0.400	0.000	0.293	1.256	8.0
	–	–	0.400	0.200	1.758	2.093	15.2
Clay*	–	–	0.400	0.000	0.251	1.256	7.4
	–	–	0.400	0.200	1.172	2.093	12.4
Peat*	–	–	0.800	0.000	0.059	0.502	5.6
	–	–	0.800	0.400	0.293	2.177	6.1
Kuantan soil <2 mm	4.7	6.5	0.566	0.014	0.110	0.937	5.9
			0.604	0.185	0.243	1.590	6.5
			0.585	0.270	0.730	1.988	10.1
Munchong soil <2 mm	10.5	11.4	0.620	0.015	0.100	0.843	5.7
			0.620	0.064	0.158	1.047	6.4
			0.630	0.088	0.180	1.129	6.6
Rengam soil <2 mm	36.6	7.7	0.589	0.004	0.111	0.854	6.0
			0.608	0.176	0.584	1.536	10.2
			0.600	0.213	0.978	1.721	12.5
Bungor soil <2 mm	22.9	33.3	0.537	0.018	0.141	1.013	6.2
			0.626	0.167	0.387	1.452	8.6
			0.592	0.222	0.866	1.765	11.6

*Average values reported by VAN WIJK and DE VRIES (1966).

Table 3. Thermal properties and density of some soil constituents*

Substance	Thermal conductivity (J/m/s/K)	Specific heat (10^3 J/m^3/K)	Density (kg/m^3)
Quartz	8.790	2 009	2 660
Clay minerals	0.293	2 009	2 650
Organic matter	0.251	2 512	1 300
Water	0.573	4 186	1 000
Ice	2.177	1 884	920
Air	0.025	1.26	1.25

*Adapted from DE VRIES (1966).

materials. This is illustrated in *Table 2,* where the data obtained from soils of Peninsular Malaysia are compared with data reported by VAN WIJK and DE VRIES (1966). Their values show that the thermal conductivity of sand is slightly higher than that of clay. The thermal conductivity of an organic soil, as represented by peat, is much lower than those of mineral materials. The volumetric heat capacity of sand does not differ from that of clay, but that for organic matter is lower. Since the heat capacities of quartz and clay minerals are the same *(Table 3),* at equal porosity and moisture content, their volumetric heat capacities are equal. But the heat capacity of organic matter is higher than those of minerals and, therefore, at equal porosity and moisture content, one would expect the volumetric heat capacity of peat to be higher than that of a mineral soil. In the example given, peat in fact has a lower volumetric heat capacity. The reason for this is that its porosity is much higher than those of the mineral soils, giving a lower percentage of solid material.

The value for damping depth depends on both the thermal conductivity and the heat capacity, and changes according to these two parameters, as can be seen in the examples in *Table 2.* Soils with higher sand contents have higher values of damping depth.

Apart from some slight variations, corresponding to differences in porosity and moisture content, the values of thermal properties obtained for the soils under study are comparable to the average values discussed above. From the results obtained for the four soils; Rengam, Bungor, Munchong and Kuantan, the effect of sand content is quite apparent. Bearing in mind the slight differences in porosity, the thermal conductivity is observed to be higher for soils with higher sand contents (for example, Bungor and Rengam), especially at high moisture contents. However, differences in damping depth are very small.

Since the organic matter content is less than 5% in all the mineral soils, its effect on the thermal properties is negligible.

Though the results of this study provide us with a better appreciation of the relationships between soil physical characteristics and thermal properties, it must be emphasized that the values of thermal properties obtained from laboratory measurements do not necessarily represent the values under field conditions. This is because laboratory samples have been disturbed and have a different structure from the field soil.

The Effect of Texture on Thermal Properties

The effect of texture on thermal properties can be attributed to differences in mineralogy and particle size. As can be seen in *Table 3,* the thermal conductivity of quartz is 30 times greater than that of clay minerals. Therefore, at equal porosity and moisture content, soils containing higher proportions of sand have higher values of thermal properties *(Table 2).*

Apart from the mineralogical makeup, this effect can also be explained by the fact that sand particles are much larger than clay particles, and thus conduct heat more readily. Heat conduction occurs at the molecular level and is enhanced by intimate contact of molecules. Even if clay particles are aggregated to form secondary particles as large as sand, heat conduction would still be greater in the sand because the sand particle is more dense. An aggregate of clay particles would be more porous and would have a lower density than a sand particle, and thus would conduct heat less readily.

The Role of Moisture in Heat Transfer in Soils

Water and solid material are much better heat conductors than air. Thus high moisture content and high density enhance soil thermal conductivity (VAN WIJK and DE VRIES, 1966; RUSSELL, 1973; LAL, 1980). However, the influence of moisture varies according to soil characteristics.

Figure 4 shows the relationship between the volumetric moisture content and the thermal conductivity of three soils of Peninsular Malaysia. The three soils differ in their sand contents, that for Rengam being 44.3%, Bungor 56.2% and Kuantan 11.2% *(Table 2).* Apart from differences in total sand content, the content of coarse sand (fraction 200 – 2 000μm) of Rengam is greater than that of Bungor *(Table 2).*

Figure 4 also shows that, at volumetric moisture contents below 0.16, the differences in thermal conductivity among the three soils are small although those with higher sand contents tend to have slightly higher values. At these low moisture

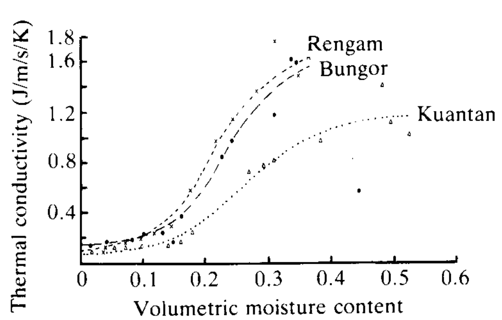

Figure 4. Change in the thermal conductivity with volumetric moisture content for Bungor, Kuantan and Rengam series soils.

contents, the amount of water is insufficient to exist as films on the soil surface.

At volumetric moisture contents greater than 0.16, the thermal conductivity increases more sharply. The differences between soils also become more apparent. At these higher moisture contents, the water films act as bridges between soil particles, providing a continuous solid-liquid path for heat conduction.

With further increases in moisture content, the thermal contact between soil particles continues to improve, until up to a certain moisture content where the thermal conductivity reaches a maximum. Moisture in excess of this critical point does not provide any further improvement to the thermal contact.

The soil with high clay content, Kuantan, reaches the maximum thermal conductivity at a higher moisture content than the other two soils. The volumetric moisture contents corresponding to the maximum thermal conductivity are 0.30, 0.33 and 0.48 for Rengam, Bungor and Kuantan respectively. For the two soils with relatively high sand contents, Bungor and Rengam, the moisture content is greater for the soil with more sand (Bungor) and apparently contradicts the earlier observation that a soil with lower sand content achieves the maximum thermal conductivity at a higher moisture content. However, although the total sand content of Bungor is higher than that of Rengam, its coarse sand content is much lower; 83% of the sand fraction of Rengam is coarse compared with 41% of that of Bungor. Thus Rengam has a smaller total surface area than Bungor, whilst Kuantan, with its high clay content has the largest surface area. Since the maximum thermal contact is achieved when all the soil particles are joined to each other by water films on the soil surface, soils with larger surface areas will require larger amounts of water. Thus, the values of volumetric moisture content mentioned above (0.30, 0.33, 0.48) increase in the order of increasing surface area (Rengam, Bungor, Kuantan).

The variation in thermal diffusivity with volumetric moisture content is shown in *Figure 5*. Soils containing more sand (Bungor, Rengam) have higher thermal diffusivity at equal moisture contents. This is because sand has a higher thermal conductivity than clay while their heat capacities are equal.

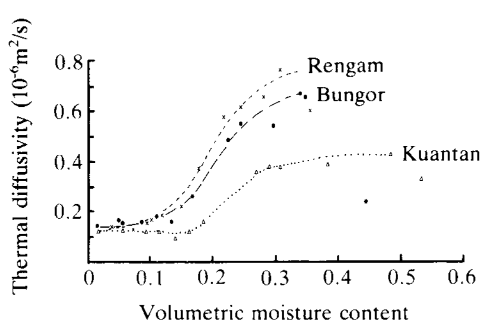

Figure 5. Change in the thermal diffusivity with volumetric moisture content for Bungor, Kuantan and Rengam series soils.

The difference in diffusivity between the soils is very large at high moisture contents. For example, at a volumetric moisture content of 0.3, the thermal diffusivity of Rengam is almost twice that of Kuantan. This shows that a difference in texture such as that between Rengam and Kuantan can contribute significantly to differences in the rate of heat transfer.

The volumetric heat capacity increases linearly with volumetric moisture content *(Tables 4–6)*. The increase is linear because the only component that increases is water, while the mineral matter and organic matter contents are constant and the bulk density is almost constant.

The Effect of Aggregate Size on Thermal Conductivity

Many of the highly weathered soils of Peninsular Malaysia are composed of stable aggregates of various sizes. Aggregate size

Table 4. Volumetric heat capacity and related parameters at various moisture contents for Bungor series soil

Moisture content (% w/w)	Total porosity (%)	Volumetric organic matter content	Volumetric mineral matter content	Volumetric moisture content	Volumetric heat capacity ($10^3 J/m^3/K$)
1.6	53.7	0.026	0.434	0.018	1 013
4.5	55.8	0.024	0.416	0.051	1 111
4.6	54.4	0.026	0.434	0.053	1 158
7.4	55.5	0.025	0.425	0.085	1 273
10.3	56.5	0.024	0.406	0.110	1 337
12.6	58.6	0.023	0.397	0.136	1 427
15.5	62.3	0.021	0.359	0.151	1 407
17.5	62.6	0.021	0.349	0.167	1 452
17.6	64.9	0.020	0.331	0.158	1 376
21.8	59.2	0.023	0.387	0.222	1 765
23.4	59.6	0.022	0.378	0.241	1 822
26.2	56.2	0.025	0.416	0.297	2 138
28.5	54.0	0.026	0.435	0.338	2 352
28.9	50.2	0.028	0.472	0.372	2 575
27.7	52.1	0.027	0.453	0.343	2 411
29.4	50.6	0.027	0.463	0.371	2 550
34.1	47.5	0.029	0.491	0.442	2 908

Table 5. Volumetric heat capacity and related parameters at various moisture contents for Kuantan series soil

Moisture content (% w/w)	Total porosity (%)	Volumetric organic matter content	Volumetric mineral matter content	Volumetric moisture content	Volumetric heat capacity ($10^3 J/m^3/K$)
1.3	56.6	0.028	0.402	0.014	937
4.7	57.0	0.028	0.402	0.055	1 108
6.6	57.4	0.028	0.402	0.072	1 180
10.1	57.7	0.028	0.392	0.108	1 311
12.8	56.6	0.028	0.402	0.141	1 468
15.7	57.0	0.028	0.402	0.160	1 549
18.0	60.4	0.026	0.374	0.185	1 590
25.1	58.5	0.028	0.392	0.270	1 988
26.9	58.5	0.028	0.392	0.289	2 068
28.7	57.7	0.028	0.392	0.308	2 149
32.5	54.3	0.030	0.430	0.383	2 544
38.3	51.3	0.032	0.458	0.481	3 012
41.6	54.0	0.030	0.430	0.490	2 989
45.7	54.0	0.030	0.430	0.538	3 191

distribution is an important factor in the thermal regime of soils because it partly determines the pore size distribution. The size and shape of pores determine the nature and number of contact points between soil aggregates.

The effects of aggregate size on the thermal conductivity of Munchong series soil are shown in *Figure 6* and *Table 7*. *Figure 6* shows the variations in thermal conductivity with volumetric moisture content for columns of aggregates of

Table 6. Volumetric heat capacity and related parameters at various moisture contents for Rengam series soil

Moisture content (% w/w)	Total porosity (%)	Volumetric organic matter content	Volumetric mineral matter content	Volumetric moisture content	Volumetric heat capacity ($10^3 J/m^3/K$)
0.4	58.9	0.030	0.380	0.004	854
3.8	58.9	0.030	0.380	0.040	1 004
7.0	60.4	0.029	0.371	0.071	1 117
9.8	61.5	0.028	0.353	0.095	1 173
11.4	59.2	0.030	0.380	0.120	1 339
11.5	60.0	0.029	0.371	0.117	1 308
15.7	64.2	0.026	0.334	0.145	1 342
17.7	60.8	0.028	0.362	0.176	1 536
20.8	60.0	0.029	0.371	0.216	1 721
23.2	58.9	0.030	0.380	0.242	1 854
25.1	56.2	0.032	0.408	0.282	2 079
26.0	54.0	0.033	0.427	0.306	2 221
28.5	52.5	0.035	0.445	0.349	2 441

Table 7. The effect of aggregate size (at equal soil porosity) on thermal conductivity (Munchong series soil samples)

Sample no.	Aggregate size (mm)	Volumetric moisture content	Porosity (%)	Thermal conductivity (J/m/s/K)
1	5–8 (90)* 2–3 (10)	0.018	69.4	0.0668
2	5–8 (70) 2–3 (30)	0.018	68.6	0.0661
3	5–8 (50) 2–3 (50)	0.016	67.7	0.0647
4	5–8 (30) 2–3 (70)	0.017	67.2	0.0613
5	>1–2 (45) 0–1 (55)	0.022	62.4	0.1122
6	>1–2 (27.6) 0–1 (72.4)	0.021	61.4	0.1051
7	>1–2 (13.8) 0–1 (86.2)	0.026	59.4	0.0987

*Values in parentheses indicate composition (%) in soil sample.

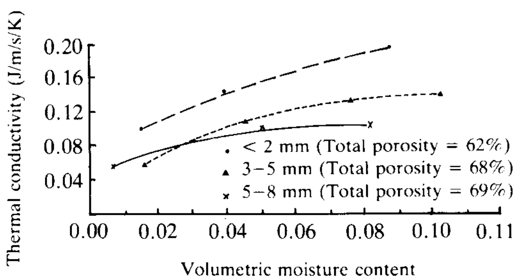

Figure 6. The effect of aggregate size on thermal conductivity at various volumetric moisture contents for Munchong series soil.

different sizes having different total porosity.

Table 7 shows the differences in thermal conductivity between various mixtures of different-sized aggregates, when both moisture content and total porosity are kept constant.

It is observed that the soil column containing aggregates < 2 mm has higher thermal conductivity than those containing larger aggregates *(Figure 6)*. The conductivity decreases as the size of aggregates increases. This trend is due to differences in the densities of the soil columns. Large aggregates create wide pore spaces and have low density. At low density, thermal contact is lower because aggregates tend to be separated by air space.

However, when porosity and moisture content are almost constant, the presence of a greater number of large aggregates tends to increase the conductivity. However, the differences in conductivity shown in *Table 7* are very small, and no definite conclusion can be drawn.

The Influence of Soil Structure on Thermal Properties

From the results obtained in this study, the influence of soil structure appears to be related to porosity, aggregate size and aggregate stability.

Low porosity results in higher thermal conductivity because of better thermal contact. A large aggregate is expected to be a better heat conductor than a group of smaller aggregates if their moisture contents and porosity are the same. A soil aggregate can be regarded as a solid body which conducts heat better than liquids and gases because the individual particles which make up the aggregate are in intimate contact.

At high moisture contents, soil aggregates are easily disrupted by physical disturbance. When this happens, the conductivity decreases because the continuity of heat flow in a solid body (soil aggregate) is broken. This phenomenon is illustrated by the points in *Figure 5* at the high range of moisture content. For Rengam, at volumetric moisture contents greater than 0.3, the thermal conductivity recorded is lower than the maximum. For Bungor and Kuantan, the drop occurs at volumetric moisture contents greater than 0.33 and 0.48 respectively. At these high moisture contents, the aggregates become less stable and break up, and become less effective as conductors of heat.

CONCLUSIONS

Differences in soil texture and structure affect the thermal properties of the soils under study, emphasizing the role of particle size in enhancing heat conduction.

Water greatly increases thermal conductivity when present in sufficient quantities to exist as films on soil surfaces. Thermal contact between particles is improved by water 'bridges'.

However, the increase in thermal conductivity due to the presence of water is greater for soils with high sand content than for clayey soils, whereas the increase in heat capacity is the same for all mineral soils. Thus, thermal diffusivity, which characterizes changes in soil temperature, increases much more for sandy soils than for clayey soils. Greater fluctuations in soil temperature are expected in soils such as Rengam and Bungor, with high amounts of coarse soil particles, than in clayey soils such as Kuantan.

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ABSTRACT

The important thermal properties of soils are defined and discussed.

In the highly weathered soils of Peninsular Malaysia, the effect of sand content on thermal conductivity and thermal diffusivity is clearly shown. Higher sand content increases the value of these variables. The effect of the grain size of the sand fraction is also clearly brought out in a comparison

between soils of the Bungor and Rengam series. The role of water in increasing the thermal conductivity and the thermal diffusivity of soils is greatly modified by the sand content. A higher sand content results in a greater increase in conductivity and diffusivity, especially in the range of volumetric water contents > 0.16.

Heat transfer is greatly reduced in soils whose aggregates were broken down due to excessive wetting. Besides aggregate stability, other elements of soil structure such as aggregate size and porosity were also shown to influence the thermal properties of soils.

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Appendix 1. Symbols and units of variables used

Symbol	Variable	Unit
C	Heat capacity	J/K
C_v	Volumetric heat capacity	$J/m^3/K$
λ	Thermal conductivity	J/m/s/K
ρ	Density	kg/m^3
a	Thermal diffusivity	m^2/s
r	Distance of heat flow from the centre of the thermocouple	m
T	Temperature	K
t	Time	s
Q	Total heat input per unit time	J/s
I	Electric current	A
R	Electrical resistance	ohm
b_1	Slope of the curve of the potential difference between the hot and cold junctions versus log t (response lag curve)	V/s
b_2	Potential difference between the hot and cold junctions per unit temperature difference (thermocouple output)	V/K
D	Damping depth	m
X_o	Volumetric organic matter content	m^3/m^3
X_w	Volumetric moisture content	m^3/m^3
X_m	Volumetric mineral matter content	m^3/m^3
ω	Angular frequency	1/s