THERMOPHYSICAL PROPERTIES OF OIL PALM EMPTY FRUIT BUNCH PEDUNCLE FOR USE AS A MULCHING MATERIAL

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ABSTRACT

The choice of mulching or topsoil covering material for the retardation of soil water loss through evaporation requires a good knowledge of thermal properties of the material. Peduncle of oil palm empty fruit bunch was obtained from some local oil palm processing units in Uyo, soaked in water and air-dried completely before shaping and subjecting samples to various laboratory tests. The bulk density, water absorption, thermal conductivity, specific heat capacity, volumetric heat capacity, thermal diffusivity, thermal effusivity and solar radiation absorptivity of the sample were found to be (332.59 ± 0.65) kg m^{-3}, $(269.54 \pm 1.28)\%$, (0.078 ± 0.001) W m^{-1} K^{-1}, (1552.56 ± 1.56) J kg^{-1} K^{-1}, (0.516 ± 0.001) MJ m^{-3} K^{-1}, (1.51 ± 0.01) 10^{-7} m^2 s^{-1}, (200.42 ± 1.33) J m^{-2} K^{-1} s$^{-1/2}$ and (15.54 ± 0.05) m^{-1} respectively in the longitudinal direction whereas the respective values were found to be (332.54 ± 0.68) kg m^{-3}, $(269.51 \pm 1.27)\%$, (0.042 ± 0.001) W m^{-1} K^{-1}, (1553.38 ± 0.44) J kg^{-1} K^{-1}, (0.517 ± 0.001) MJ m^{-3} K^{-1}, (0.82 ± 0.01) 10^{-7} m^2 s^{-1}, (147.98 ± 1.57) J m^{-2} K^{-1} s$^{-1/2}$ and (21.06 ± 0.18) m^{-1} in the transverse direction. The results of the tests favour the peduncle as a potential mulching material for retardation of soil water loss through evaporation and a slow response to changes in its thermal environment.

INTRODUCTION

Plants are photoautotrophs. They are grown on soils which have all the elements needed for the preparation of their food, including water, employing solar energy. A plant absorbs light from the solar system, water from the ground, and carbon dioxide gas derived from the atmosphere for the preparation of its food (Garg and Garg, 2018).

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A plant absorbs only part of the energy from the solar system, whereas the remaining part of the energy from the solar system is lost as heat and fluorescence. The photon energy that is within the range of light wavelength suitable for photosynthesis, is designated as photosynthetically active radiation (PAR) (Etuk *et al.*, 2016a; 2016b; Liu and van Iersel, 2021; Mõttus *et al*, 2012; Ross and Suler, 2000).

It is expedient to point out that solar energy is a requirement for the sustenance of plant life, which depends on seasons, latitude and cloud cover, among other factors. The majority of this energy is ineffective for plants and instead heats the earth, atmosphere, and, in some cases, reflects from the earth (Garg and Garg, 2018). The proportion of solar energy which heats the earth gives rise to evapotranspiration of soil water, arising from crop transpiration and soil evaporation. Evaporation of soil water in non-irrigated areas has some adverse effects on plants. This situation calls for adequate

mulching to reduce or slow down the rate of soil evaporation for the nourishment of plant life, during dry season (Kakaire *et al.*, 2015). The rate of heat transport through the mulching material(s) should be considered when selecting the material(s). More so, high temperatures are known to hasten the ripening, senescence and withering of crops. A long duration of severe heat energy is capable of causing some crops to go into dormancy. This, coupled with the evaporation of soil water, will result in moisture stress, which may cause perpetual dormancy (FAO, 1998). This research, therefore, seeks to examine some thermophysical properties of oil palm empty fruit bunch (EFB) peduncle to establish its mulching suitability against evaporation during the dry season in non-irrigated farmlands. The peduncle of EFB is obtained from oil palm tree, scientifically named *Elaeis guineensis*. The oil palm tree belongs to Arecaceae palm family in the Plantae kingdom of Arecales order. The plant has Africa as its origin (Verheye, 2010) and it is said to originate from the tropical rainforest zone. Indonesia is said to be the largest exporter of palm oil (Murphy, 2007; Ziaei and Ali, 2021).

Theoretical Considerations

Ekpe and Akpabio (1994) stated that several factors, including geographic and site characteristics as well as thermophysical properties, would determine the soil temperature. Evapotranspiration is a combination of the evaporation of water from the soil and the transpiration of water from leaves. It is determined by environmental soil and air conditions. According to the report of the Food and Agriculture Organization of the United Nations (FAO, 1998), the crop coefficient changes with the variations in ground cover, during the crop growing period. The evaporating power of the atmosphere affects the initial crop coefficient. Transpiration in some plants happens to be very low because such plants close their stomata during the day and open them at night. In such situations, transpiration is low whereas losses of water are mainly from the evaporation of the soil. Hence, the bulk of crop evapotranspiration under standard conditions from such plants is through evaporation from the soil. A typical example of a plant with such behaviour is pineapple. It is only with a full ground cover that soil evaporation can be reduced, leading to a single crop coefficient for mid-season. This mid-season crop coefficient value would be lower than at the initial stage, since it occurs during full ground cover.

Ekpe and Akpabio (1994) and Keunbo *et al.* (2020) attributed that the changes in temperature of soil with depth are due to various factors, including the quantum of radiant energy that gets to the surface of the soil, thermal properties of the soil, and colour of the soil. The amount of absorbed radiant energy

leads to changes in soil temperature. Heating the air above the soil would raise the surface temperature, heating the interior layers of soil and radiating to the atmosphere, which may occur as a result of absorbed soil surface energy. Robert *et al.* (2020a) expressed the heat budget as Equation (1):

Heat flow through the soil = Absorbed solar radiation + Heat absorbed from the atmosphere - Re-emitted radiant energy   (1)

The heat balance equation above, in one dimension, can be expressed as Equation (2) (Khaty *et al.*, 1978):

$$-k \left(\frac{\partial T}{\partial x}\right)_{x=0} = h(T_{atm} - T_{x=0}) + \alpha I - \varepsilon \Delta R \qquad (2)$$

where k is soil thermal conductivity, T is soil temperature, h is surface heat transfer coefficient, T_{atm} is air temperature in the atmosphere, α is solar radiation absorptivity at the soil surface, I is solar radiation intensity, ε is long-wave emissivity of the soil surface, and ΔR is the difference between the incident long-wave radiation and the soil surface emitted radiation.

Giving solar temperature, T_s as Equation (3):

$$T_s = T_{atm} + \left(\frac{\alpha I}{h}\right) - \left(\frac{\varepsilon \Delta R}{h}\right) \qquad (3)$$

Considering the above equation, Sohda *et al.* (1979) and Moustafa *et al.* (1981) expressed:

$$T(x,t) = \alpha_0 + \sum_{m=1}^{\alpha} \{\alpha_m \, exp[i(m\omega t + \alpha_m x]\} \qquad (4)$$

as a general solution to one-dimensional heat conduction

Equation (4) results in Equation (5):

$$T(x,t) = \alpha_0 + \sum_{m=1}^{\alpha} \{\alpha_m \, exp\,(-\alpha_m x) \, Cos\,(m\omega t - \alpha_m x)\} \qquad (5)$$

as its real part, with $\alpha_m = \left(^{m\omega pc}/2k\right)^{\frac{1}{2}} (1-i)$

where $\omega = 2\pi/period$.

With the modification of Equation (5), a more convenient expression showing the variation of soil temperature with thickness of soil yields, as Equation (6):

$$T(x,t) = T_m - A_s \, exp\,(-ax) \, Cos\{w(t-t_0 - {}^{ax}/_w)\} \qquad (6)$$

where A_s is daily temperature amplitude (in °C at $x = 0$), x is thickness of the soil, t is time of the day (in hours), t_0 is time corresponding to the minimum temperature at the soil surface (in hours). T_m can be computed from the hourly soil surface temperature

average, T_{hss} on a 24-hour period in °C employing, Equation (7):

$$T_m = \sum_{m=1}^{24} \left({}^{T_{hss}}/_{24} \right) \qquad (7)$$

This results in the expression of Equation (8):

$$T(x,t) = T_m - A_s \exp(-ax) \, Cos\{(^\pi/_{12})[t = t_0 - (^{12ax}/_\pi)]\} \qquad (8)$$

MATERIALS AND METHODS

Materials Collection and Sample Preparation

Several undecayed EFBs of oil palm were collected from some local oil palm processing units in Uyo Local Government Area, Akwa Ibom State, Nigeria. The peduncle was removed from each bunch (*Figure 1*) before being sorted. Those wider than 114 mm in diameter were chosen for use in this study. The selected ones were then soaked in cold water for 48 hr to remove any accompanying impurities. The soaked peduncles were removed from the water after 48 hr and each of them was suspended with a string to hang freely to dry in the atmosphere. Circular pieces were prepared from longitudinal and transverse sections of the peduncles. The pieces were identical, with a thickness of 9 mm and a diameter of 110 mm. In all, five of such pieces were prepared each from the longitudinal section and transverse section. They were then sun-dried completely, coded (for ease of identification), and then used as test samples in this work.
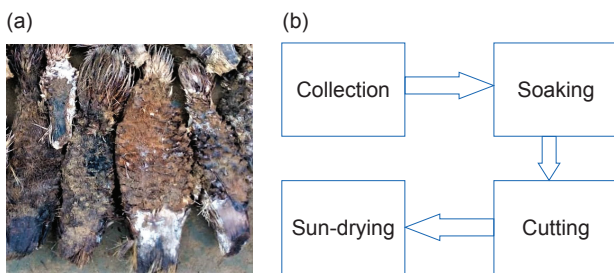

Figure 1. (a) Peduncles of oil palm empty fruit bunch, and (b) steps of sample preparation.

Property Tests

The thermal conductivity of each test sample was determined by using Modified Lee–Charlton's Disc Apparatus Technique as described in details elsewhere by Robert *et al.* (2021a) and obtained based on the relation in Equation (9):

$$k = \left(\frac{Mcx}{A\Delta\theta} \right) \frac{dT}{dt} \qquad (9)$$

where M is mass of the disc, c is specific heat capacity of the disc, x is test sample's thickness, A is

cross-sectional area of the sample, $\Delta\theta$ is temperature across the test sample's thickness and $\frac{dT}{dt}$ is rate of cooling of the disc.

After that, the samples were cut into reasonable sizes and shapes required for other tests. The modified water displacement method, proposed by Robert *et al.* (2019) was used for the bulk density test. The mass of each sample was measured using a digital weighing balance (S. METTLER - 600 g) after which its value was divided by that of bulk volume (Etuk *et al.*, 2018; Robert *et al.*, 2021b; 2021c) to obtain the required bulk density. The samples were then weighed for water absorption investigation. Then, 10 identical vessels were filled with equal volumes of water, initially at 28ºC, and the samples were immersed separately in water. They were removed from the water after 24 hr and allowed to surface-dry. The samples were then re-weighed and water absorption was calculated using the formula (Robert *et al.*, 2020b).

$$WA = \left(\frac{M_w - M_d}{M_d} \right) 100\% \qquad (10)$$

where M_d is mass before immersion, M_w is mass after immersion, and WA is water absorption.

Specific heat capacity was measured for each sample with the aid of SEUR'S Apparatus (Etuk *et al.*, 2020). In this study, the device was designed with a central square cavity measuring $60 \times 60 \times 14$ mm for heat exchange. The heat exchange plates were aluminium, test samples, and plywood materials each of which was cut to a square of almost similar dimensions (for length and width) as the cavity but with a consistent thickness of about 8 mm. During heat exchange, the hot aluminium plate was sandwiched between the test sample and plywood plate until the system attained thermal balance. Temperature monitoring and measurements were conducted by using three digital thermometers (Model 305, calibrated and equipped with a Type-K probe). The obtained data were then used to compute the value of specific heat capacity, C based on the relation in Equation (11):

$$C = \frac{Q_a - Q_p}{M_s \delta T} \qquad (11)$$

where Q_a is quantity of heat lost by the aluminium plate, Q_p is quantity of heat gained by the plywood, M_s is mass of the sample, δT is rise in temperature of the sample.

Corresponding volumetric heat capacity, was determined for the test samples from the values of bulk density and specific heat capacity as suggested by Robert *et al.* (2022):

$$C_v = \rho C \qquad (12)$$

where ρ is bulk density.

Thermal diffusivity value, was computed using the equation (Cengel *et al.*, 2012; Etuk *et al.*, 2010; Rajput, 2015; Welty *et al.*, 2001):

$$\lambda = \frac{k}{\rho C} \qquad (13)$$

Solar radiation absorptivity and thermal effusivity were computed using the values for other related parameters already obtained. The value of solar radiation absorptivity, α was computed on a 24 hr periodic basis employing the equation expressed by several authors, including Ekpe and Akpabio (1994) and Robert *et al.* (2020a) as:

$$a = \sqrt{\frac{w}{2\lambda}} \qquad (14)$$

whereas thermal diffusivity value, was calculated using the formula:

$$e = \sqrt{k\rho C} \qquad (15)$$

RESULTS AND DISCUSSION

The experimental values determined per test carried out on the test samples are expressed in *Table 1*. It can be seen from the table that the bulk density of the test samples ranges from 331.65 to 333.24 kg m^{-3} while that of soil samples was reported to be between 1000.00 kg m^{-3} and 2000.00 kg m^{-3} (Birkeland, 1984; Blake and Hartge, 1986; Purser 1988), indicating that samples were far less dense than soil samples. This also shows that the degree of compactness of particles is equally far less compared to that of any soil sample. Hence, it allows for good aeration and supports permeability, a situation that accounts for a higher percentage of water absorption. Measurement of bulk density is vital in quantitative studies relating to soil, as it is a necessary parameter for computing soil moisture movement within a profile. Variation in bulk density of soil is attributable to the relative proportion and density of solid organic particles as well as porosity. It is plausible that the test sample if applied as a mulching material, will make the soil less dense.

The results clearly show thermal conductivity values of 0.074 ± 0.001 W m^{-1} K^{-1} for the test sample when subjected to heat flow in the longitudinal direction, and 0.042 ± 0.001 W m^{-1} K^{-1} when in the transverse. This can be explained in terms of the low bulk density value and availability of a high degree of still air space, which equally accounts for the low bulk density. Bulk density has a direct relationship with the thermal conductivity of the samples. This is because, the more the percentage of dead air space (still air volume) in the samples, the bulk density will be lower and hence, lower their thermal conductivity since air is a good heat insulant. Our finding is supported by the report of the United State

TABLE 1. EXPERIMENTAL RESULTS OF THE PROPERTY TESTS PERFORMED ON THE OIL PALM EMPTY FRUIT BUNCH PEDUNCLE

Tests section	Sample code	Bulk density ($kg m^{-3}$)	Water absorption (%)	Thermal conductivity ($W m^{-1} K^{-1}$)	Specific heat capacity ($J kg^{-1} K^{-1}$)	Volumetric heat capacity ($MJ m^{-3} K^{-1}$)	Thermal diffusivity ($10^{-7} m^2 s^{-1}$)	Thermal effusivity ($J m^{-2} K^{-1} s^{-1/2}$)	Solar radiation absorptivity (m^{-1})
Longitudinal	SL1	332.93	268.88	0.078	1556.76	0.518	1.50	201.06	15.57
	SL2	330.78	272.01	0.076	1550.24	0.513	1.48	197.41	15.68
	SL3	333.14	269.43	0.079	1552.33	0.517	1.53	202.12	15.42
	SL4	331.99	271.76	0.076	1545.41	0.513	1.48	197.47	15.68
	SL5	334.02	265.61	0.080	1558.04	0.520	1.54	204.04	15.37
	Mean ± Std error	332.59 ± 0.65	269.54 ± 1.28	0.078 ± 0.001	1552.56 ± 1.56	0.516 ± 0.001	1.51 ± 0.01	200.42 ± 1.33	15.54 ± 0.05
Transverse	ST1	331.79	271.83	0.042	1554.03	0.516	0.81	147.16	21.19
	ST2	332.83	269.13	0.043	1553.61	0.517	0.83	149.11	20.93
	ST3	334.13	265.74	0.044	1554.33	0.519	0.85	151.17	20.68
	ST4	330.71	272.10	0.040	1552.83	0.514	0.78	143.32	21.59
	ST5	333.25	268.75	0.043	1552.11	0.517	0.83	149.14	20.93
	Mean ± Std error	332.54 ± 0.68	269.51 ± 1.27	0.042 ± 0.001	1553.38 ± 0.44	0.517 ± 0.001	0.82 ± 0.01	147.98 ± 1.57	21.06 ± 0.18

Department of Agriculture (USDA) Forest Products Laboratory on thermal conductivity of wood, which shows that density and grain direction, among other factors, affect the thermal conductivity of a wood sample. The thermal conductivity value obtained either in the longitudinal or transverse direction indicates that the sample as a ground cover or mulching material retards heat transport on the soil it covers. However, the transverse sample exhibits more pronounced heat retardation compared to the longitudinal sample. Thermal conductivity is very important as far as thermal transport is involved (Incropera and De Witt, 1990). The values of thermal conductivity for straw and sawdust were reported as 0.0576 W m^{-1} K^{-1} for straw and 0.0649 W m^{-1} K^{-1} for sawdust (Perry and Green, 2007; Powell and Childs, 1972; Sayigh, 1978). It can be inferred that, transversely, the sample has a mean thermal conductivity value which is 27% less than the thermal conductivity value of straw and 35% less than that of sawdust. However, the mean thermal conductivity value of the sample is higher than that of straw by 22% and that of sawdust by 12% when considered in a longitudinal direction to the flow of heat.

The mean specific heat capacity of about 1552.56 J kg^{-1} K^{-1} was obtained for the samples in the longitudinal direction whereas 1553.38 J kg^{-1} K^{-1} was recorded for the ones selected for transverse observation. This suggests that the test sample has an approximate specific heat capacity of 1550 J kg^{-1} K^{-1}. This specific heat capacity result is comparable with the observation of Kodešová *et al.* (2013) on the specific heat capacity of soil organic matter reported as being 1900 J kg^{-1} K^{-1}. Theirs was a little higher than ours, possibly because of the presence of soil particles in soil organic matter. It can be adjudged from the results that about 0.516 MJ needs to be added in the form of heat to one unit of volume of the test sample to cause an increase of one unit of its temperature, as shown in its volumetric heat capacity value. Comparatively, the result of the volumetric heat capacity of the sample was far less than the value reported for *Miscanthus* biochar, as 2.3348 MJ m^{-3} K^{-1}; switchgrass biochar, as 2.2232 MJ m^{-3} K^{-1} and wood chip biochar, as 0.00939 MJ m^{-3} K^{-1} (Behazin, 2016).

The thermal diffusivity of plant-based materials is generally much smaller than that of other materials like stone, metals and others. For the studied samples, the mean thermal diffusivity value was 1.51×10^{-7} m^2 s^{-1} in the longitudinal direction and 0.82×10^{-7} m^2 s^{-1} in the transverse direction. The low thermal diffusivity expresses how sluggish the test sample can absorb heat from its surroundings. Thermal diffusivity is the ratio of thermal conductivity to the product of bulk density and specific heat capacity. Herewith, the low thermal conductivity, coupled with the moderate

mean bulk density and specific heat capacity of the sample, enable the thermal diffusivity value of the sample to be lower than that of wood chip biochar, which was 2.9426 ± 0.1437 m^2 s^{-1} (Behazin, 2016). Thermal diffusivity is an important indicator of thermal insulating behaviour. Since the test sample exhibits low thermal diffusivity, which was even lower than that reported for soil samples, it therefore suggests that it can be very useful as a retardant of soil water evaporation during the summer or dry season.

A material's thermal effusivity (also known as the thermal inertia or thermal responsivity of a material) is a measure of its ability to exchange thermal energy with its surroundings. In the longitudinal direction, the samples have a thermal effusivity value of about 200 J m^{-2} K^{-1} s$^{-1/2}$. The thermal effusivity values of the samples in this research are within the range for wood samples. Wood has a low thermal effusivity value in J m^{-2} K^{-1} s$^{-1/2}$ whereas metals have high thermal effusivity values in kJ m^{-2} K^{-1} s$^{-1/2}$. This is supportive of the test sample as a potential mulching material. Considering solar radiation absorptivity, the sample has a mean value of 15.54 m^{-1} in the longitudinal direction to the flow of heat, whereas a mean value of 21.06 m^{-1} was obtained in the transverse direction. The results yield about 26.16% decrements in the value of solar radiation absorptivity in longitudinal as compared with transverse. As far as solar radiation absorptivity is concerned, the mean value suggests that the test sample is better in the transverse direction than in the longitudinal direction.

Variation in soil temperature, as aforementioned, is influenced by the amount of solar radiation that reaches and is absorbed by the soil. Since the test sample is expected to receive solar radiation when applied as a soil surface cover, it implies that the variation of the sample's temperature will depend on the quantum of solar radiation it receives and absorbs. Now, revisiting our Equation (8), and substituting the mean values of solar radiation absorptivity into it gives rise to the following models:

For application of the sample in the longitudinal direction,

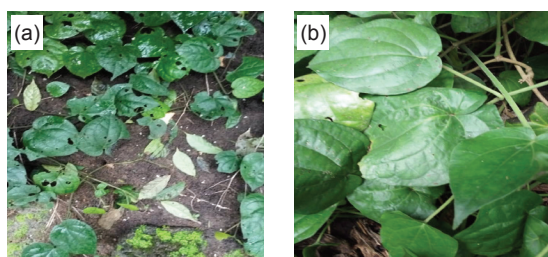$$T(x,t) = T_m - A_s \exp(-15.54x) Cos \{(0.262)[t - t_0 - (59.35x)]\} \tag{16}$$

For application of the sample in the transverse direction,

$$T(x,t) = T_m - A_s \exp(-21.06x) Cos \{(0.262)[t - t_0 - (80.43x)]\} \tag{17}$$

These can be applied to predict temperature variation of peduncle of oil palm empty fruit bunch in a chosen direction of placement taking into

consideration its thickness, *x* at any time, *t* of the day.

According to Shafiquzzaman and Naher (2017), oil palm fibres are easily degraded, environmentally friendly, and nutrient-rich, once formed. They also posited that bio compost, apart from being a good biofertiliser, is a good biocontrol agent against soil-borne pathogens. Their report and that of Baharuddin *et al*. (2009) show that soils that were initially slightly acidic were found to be alkaline with an electrical conductivity range of between 40.10 S cm^{-1} and 50.40 mS cm^{-1} with improved C:N ratio, percentage nitrogen (N), phosphorus (P), and potassium (K), causing the bio composting of oil palm fibres to exhibit great potential as soil micronutrient enhancers and improve plant growth performance and crop yield production. The above is supported by the report of Kavitha *et al*. (2013) that suggests an empty oil palm fruit bunch demonstrates an improved C:N ratio with an increase in the macronutrients such as NPK as well as micronutrients including zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn). Hence, oil palm EFB has a positive effect in terms of nutrients in the soil and plant growth (Liew *et al*., 2010; Tao *et al*., 2018; Trisakti *et al*., 2017; Zaharah and Lim, 2000). The above are added advantages to the test sample as a potential mulching material. Apart from the retardation of water evaporation from the soil, this means that the test sample is degradable in nature, very rich in soil nutrients, and improves the pH of the soil. This is supported by the report of Triyono and Haryanto (2019). *Figure 2* shows that the soil mulched with our test sample enhances the growth of a crop planted on it.

For comparison with the results obtained in this study, the values of thermal transport and thermodynamic properties of some related materials are adopted as presented in *Table 2*. As shown, the specific heat capacity of the test samples was greater than the values reported for soil minerals and air. Also, the samples were observed to be lighter than any of the materials listed in *Table 2*.

CONCLUSION

This research work was aimed at investigating the thermophysical properties of the peduncle of an oil palm empty fruit bunch for the purpose of among others, using it as mulching material for retardation of soil water loss by evaporation; protecting soils from wind, water, and traffic-induced compaction and erosion; conserving soil moisture; increasing water detention capacity; providing for good aeration and supporting permeability. The results of thermophysical properties, as well as density, are indications that the test sample can slow down heat flow, respond sluggishly to changes in its thermal environment and render storage of thermal energy difficult, therefore, retarding soil water loss. Generally, it was found that the sample is a potential mulching material suitable for soil cover for enhancement of crop performance and production. Herewith, we recommend that the peduncle of the oil palm empty fruit bunch can be used by farmers as a mulching material for topsoil covering which will address the problem of environmental pollution as a result of the usage of inorganic fertilisers.

Figure 2. The crop grown on soil (a) without the peduncle, and (b) mulched with the peduncles.

TABLE 2. THERMODYNAMIC AND TRANSPORT PROPERTIES OF SOME RELATED SOIL MATERIALS (at 20°C)

Soil component	Density (Mg m^{-3})	Specific heat (kJ kg^{-1} K^{-1})	Volumetric heat capacity (MJ m^{-3} K^{-1})
Soil minerals (average)	2.6500	0.73	1.9000
Soil organic matter (average)	1.3000	1.90	2.5000
Water	1.0000	4.18	4.1800
Air	0.0012	1.00	0.0012

Source: Van Wijk and De Vries (1963).

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