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Comparison of Heat Transfer Properties of Dry Sand and Magnesium Oxide Powder by Single-Probe Method

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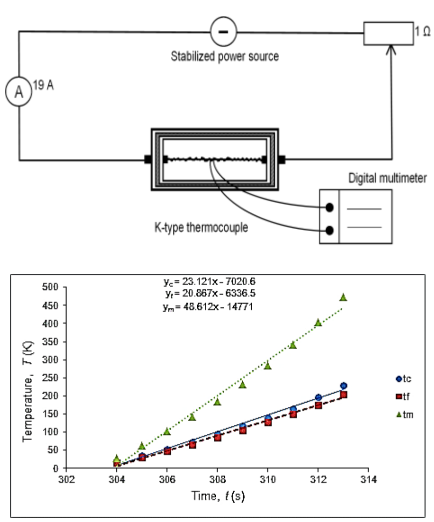
Graphical abstract



Abstract

The use of magnesium oxide (MgO) powder in electrical heating appliances is based on its thermal and electrical insulating properties. However, dry sand, which is readily available and free on the surface horizon than MgO powder also possesses good thermal and electrical insulating properties that could be utilized in the fabrication of electrical heating devices. In this study, we determined and compared heat transfer properties of dry fine-medium sand (0.125-0.50 mm) and dry coarse sand (0.50-1.00 mm) with those of MgO powder, using the single-probe method. Electrical heating equipment was designed and fabricated with a heating element that generated a heat flux of $18.05 Wm^{-1}$. From the results obtained, the thermal conductivities of dry fine-medium sand, dry coarse sand and MgO powder were found to be 0.21 $m^{-1}K^{-1}$, 0.22 $Wm^{-1}K^{-1}$ and 0.36 $Wm^{-1}K^{-1}$ respectively. Temperature increase per second were also obtained and found to be 4.75×10^{-2} Ks^{-1} in dry fine-medium sand, 4.28×10^{-2} Ks^{-1} in dry coarse sand and 2.03×10^{-2} Ks^{-1} in MgO powder. Thus, while it took MgO powder 472 s to warm from 30 °C to 40 °C, it took dry coarse sand and dry fine-medium sand only 229 s and 205 s respectively to warm through the same temperature range.

Keywords: Thermal conductivity, temperature, heater, sand, single probe

1.0 INTRODUCTION

Heat transfer properties of different soils, including dry sand, have been determined in both fields and laboratory settings by many researchers [1-4]. However, studies on thermal conductivities and rate of temperature increase through dry sand samples in comparison with those of MgO powder, for the sole purpose of recommending them as alternative insulators in electrical heating devices, is yet to receive the attention of soil physicists, geologists and engineers.

Electrical heating appliances, such as kettles, electric irons and electric immersion water heaters have found useful applications in households, industries, business outlets and other stand establishments. The insulator used in these heaters is MgO powder [5]. Evidently, MgO powder is not as available and free on the surface horizon as dry sand. Dry sand is comparatively cheaper, available and would not require tedious pre-treatment processes. It can therefore serve as an important thermal conductor and as electrical insulator in a supposed heater case such as steel or copper tube. This is possible due to the fact that soil thermal properties such as thermal conductivity have been found to have great impact on subsurface heat transport [6].

Thermal conductivity of sand has been determined by different experimental methods and model equations. Thermal conductivity of dry sand was obtained as 0.27 $Wm^{-1}K^{-1}$ [2] in a laboratory experiment. Also, a semi-empirical equation was developed [7] and applied to calculate thermal conductivity of dry sand as 0.24 $Wm^{-1}K^{-1}$. The factors which affect thermal conductivities of sand and all soil types includes particle size, moisture contents, presence of organic matter and temperature, etc [8]. Thus, it was found that thermal conductivity of sand increases with increase in its particle size. In a more recent study [9], it was found that thermal conductivity of soil is influenced by its state of aggregation, of which particle size forms a part.

The purpose of this study was to determine and compare heat transfer properties (thermal conductivity and rate of temperature increase) of dry coarse sand (0.50-1.00 mm) and dry fine-medium sand (0.125-0.50 mm) with those of MgO powder. A simple laboratory single-probe method was adopted. Similar method has been used in a laboratory setting to determine and compare thermal conductivities of Jordanian soils at different moisture contents [1]. The heating equipment used in that study generated heat fluxes of about 11 to 12 Wm^{-1}. For this study, electrical heating equipment was designed and fabricated out of thin sheets of mild steel. Embedded in the equipment was a length of a heating element which generated a heat flux of 18.05 Wm^{-1}. This showed an increase of 6.05 to 7.05 Wm^{-1} above the one used in [1]. Making use of Chromel –alumel thermocouple, well connected to a digital multi-meter, values of temperature data were obtained at 15 s intervals, starting from 90 s to 300 s. Here, temperature data with less than 90 s of heating time period were excluded from records to avoid errors due to thermal contact resistance between the material of the thermocouple probe and the surrounding sample [2]. As sandy soil is heated, the temperature response is increasingly a function of surrounding sand [10]. This is also in agreement with the findings made in [11]. It has also been reported that thermal conductivity of soils increases with increase in moisture content [1] but decreases if the percentage of organic matter by weight in sand increases [12]. Moist sand cannot be used as an electrical insulator for obvious reasons. However, based on these findings, the sand sample used in this study was washed with hydrogen peroxide to destroy any trace of organic matter in them.

MgO powder on the other hand, has thermal conductivity values which increase with increase in temperature. In this study, it was found that, although thermal conductivity of MgO powder was higher in magnitude than those of dry sand samples, rate of temperature increase through it has been found to be slower .This is in line with the findings made [13] when determining thermal conductivities of dry soils that, the higher the thermal conductivity of the soils, the lower the rate of temperature increase detected with the thermocouple. Since rate of temperature increase is an important factor in determining the energy consumed by an electrical heating appliances, it will be expected that designing and fabricating electrical heating devices with dry coarse sand (0.50-1.00 mm) and dry fine-medium sand (0.125-0.50 mm) as electrical insulators and as thermal conductors will be of higher economic importance over the conventional types.

2.0 THEORETICAL

In a The empirical law of heat conduction based on experimental observation originated from Biot [14], but it was generally named after a French Mathematical Physicist, Joseph Fourier, who used it in his analytical theory of heat. This law states that the flux of conduction is the product of thermal conductivity of medium and the temperature gradient in the medium.

Consider a rectangular box containing a uniform sandy soil material having length *L* and cross-sectional area *A*. The quantity of heat flow per second from one end of the material to the other end at temperature T_2 is given by:

$$\frac{Q}{t} = KA\frac{T_2 - T_1}{L} \tag{1}$$

A useful form of this equation is

$$q = \frac{Q}{At} = K\frac{T_2 - T_1}{L} \tag{2}$$

where q is the heat flux, K is the thermal conductivity of sand or sampled material and A is the area.

Differentiating, equations (1) and (2), we have

$$q\frac{1}{A}\frac{dQ}{dt} = -k\frac{dT}{dL}$$

Therefore

$$q = -k\frac{dT}{dL} \tag{3}$$

The temperature gradient, $\frac{dT}{dL}$, being negative since temperature diminishes as L increases.

In a single probe method, however, the temperature response is measured during heating and the thermal conductivity is derived from a simplified analytical solution of heat conduction equation. The thermal conductivity can be closely approximated with the single-probe method by the following formula [3]:

$$K = \frac{q}{4\pi s_1} \tag{4}$$

where q is the energy input per unit length of heater per unit time (measured in Wm^{-1}) and s is the slope of regression between measured temperature and the natural log of time (see Figure 5).

i.e.

$$S_1 = \frac{\Delta T}{\Delta \ln t}$$

Equation (4) now becomes:

$$K = \frac{q}{4\pi}\left(\frac{\Delta \ln t}{\Delta T}\right) \tag{5}$$

If $q = I^2R$, K can be calculated from;

$$K = \frac{I^2 R \Delta \ln t}{4\pi \Delta T} \tag{6}$$

where $\frac{I}{S_1} = \frac{\Delta \ln t}{\Delta T}$ and since $\frac{I}{4\pi} = 0.0769$

We have;

$$K = 0.0769 \frac{I^2 R}{S_1} \tag{7}$$

Temperature increase per second is given by the slope, S_2

$$S_2 = \frac{\Delta T}{\Delta t} \tag{8}$$

S_2 can be obtained from a graph of temperature through sampled materials against time (see Figure. 5).

3.0 MATERIALS AND METHOD

A Sample of dry sand was collected and prepared for particle size analysis. The sandy soil sample was first washed with clean water and then with hydrogen peroxide. The H_2O_2 destroys any organic matter present in the sample [12]. The sample was rewashed with water and sun dried. The sand sample was sieved using five different sieves of aperture 2.00 mm, 1.00 mm, 0.50 mm, 0.25 mm and 0.125 mm. From particle-size analysis, dry fine-medium sand (0.125-0.50 mm) and dry coarse sand (0.50-1.00 mm) were obtained. MgO powder sample was also obtained.

In order to make use of the single probe method to determine the thermal conductivities and temperature increase per second through the samples, mild steel sheets were used to fabricate a rectangular box with dimensions of length 19.00 cm, width 4.00 cm and height 3.00 cm. The two ends of the box were drilled centrally and a line heat source of resistance 5 Ω was inserted length-wise through the two holes via two insulating rubbers fixed at both ends of the heat source, a short distance away from the rubbers, and stretched so that it remained horizontally stiffed in the heating equipment. A narrow hole was drilled on one side of the box for easy insertion of a chromel-alumel thermocouple probe (K-type) whose terminals were connected to a digital multimeter. The multimeter was connected to the circuit to record temperature increase at specified time interval in degree Celsius. Figure 1 illustrates the complete assembly of the heating equipment used for this study. The equipment was well lagged to ensure even distribution of heat as suggested in [15]. To determine the heat transfer properties of the samples, the circuit was connected as shown in Figures 2 and 3.

Each sample was released into the box one after the other and measurements of temperature increase with time through the sample was taken accordingly. A stabilized power source produced a constant current of 19.00 A through the heater. Temperatures T (K) were measured and recorded every 15 s, starting from 90 s of heating up to 300 s. The current passing through the heater was measured with an ammeter connected in series with a resistor of resistance 1.0 Ω. The power or quantity of heat flow through the heater was obtained from the product of the square of current and the resistance of the heater ($q=I^2R$) which was found to be 18.05 Wm^{-1}.

Time taken for every 1 °C increase in temperature for the three samples was recorded, starting with ambient temperature of 30 °C. Time taken for the temperature of each of the three samples to rise from 30 °C to a maximum temperature of 40 °C was also recorded. Temperature increase per second was obtained from the slope of regression of measured temperature T (K) and time t(s) in each case using equation 8.

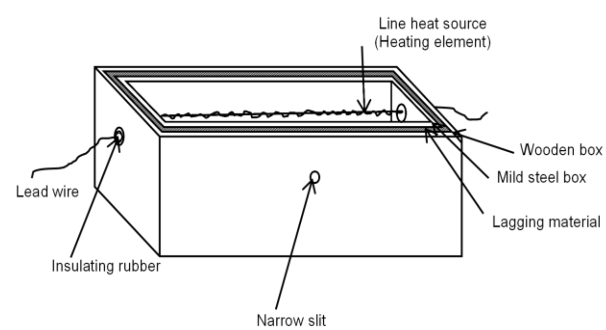


Figure 1 Schematic diagram of the electric heating equipment

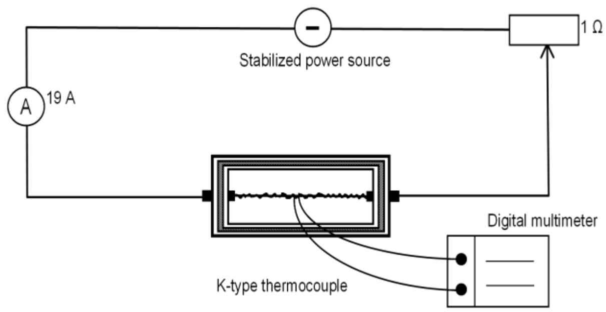


Figure 2 Schematic diagram of experimental setup

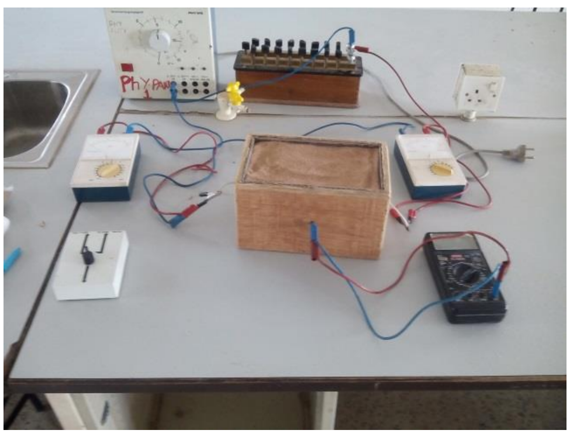


Figure 3 Picture of experimental setup

4.0 RESULTS AND DISCUSSION

The Results of the experiments conducted are shown in the plots presented in Figures 4 and 5. It can be seen (from Figure 3) that, after 300 s of heating, each of the three samples attained different magnitudes of temperatures. Their thermal conductivities were therefore calculated (using equation 7) at their respective temperatures and found to be 0.21 $Wm^{-1}K^{-1}$ at 13.4 °C for dry fine-medium sand, 0.22 $Wm^{-1}K^{-1}$ at 12.7 °C for dry coarse sand and 0.36 $Wm^{-1}K^{-1}$ at 7.4 °C MgO powder. Hence, while dry fine-medium sand and dry coarse sand reached a maximum temperature of 13.4 °C and 12.7 °C respectively after 300 s of heating, MgO powder, reached a maximum temperature of 7.4 °C only after the same time under same heat flux of 18.05 Wm^{-1}. The slight difference in thermal conductivities of the two dry sand samples was due to the difference in their particle size [1]. It is therefore evident (see Figure. 4) that thermal conductivity of dry coarse sand is greater than that of dry fine medium sand by an order of 0.1 $Wm^{-1}K^{-1}$. However, heat flow through dry fine-medium sand is faster than through dry coarse sand.

From the graph in Figure 5, slopes, S_2 gave values of temperature increase per second $(\Delta T/\Delta t)$ using equation 8 and are found to be 2.03 x10^{-2} Ks^{-1} for MgO powder, 4.28 x 10^{-2} Ks^{-1} for dry coarse sand and 4.75 x 10^{-2} Ks^{-1} for dry fine-medium sand. Thus, while it took dry fine-medium sand only 205 s when heated up to 10 °C above its ambient temperature of 30 °C, it took dry coarse sand 229 s to be heated to 10 °C above same ambient temperature using same heat flux provided by the heating equipment. Heat flow was observed to be slowest in MgO powder as it covered a period of 472 s when heated to 10 °C above its ambient temperature of 30 °C.

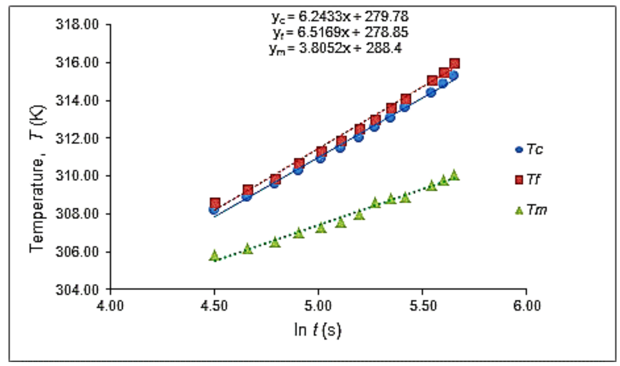


Figure 4 Graph of temperature variations of the three samples; dry coarse sand (T_c), dry fine-medium sand (T_f) and MgO powder (T_m) versus natural log of time (ln t). y_c, y_f and y_m are the respective trend line linear equations for T_c, T_f and T_m

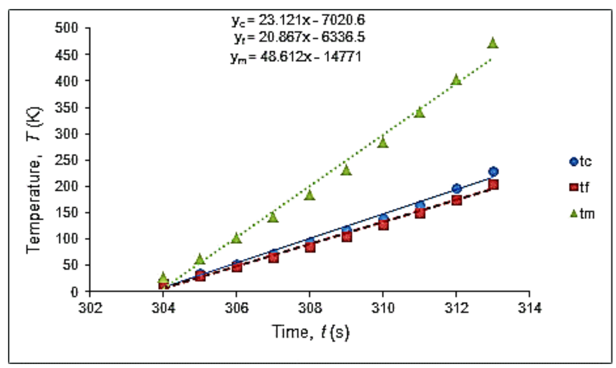


Figure 5 Graph of temperature (T) versus time taken to attain temperature for dry coarse sand (t_c), dry fine-medium sand (t_f) and MgO powder (t_m). y_c, y_f and y_m are the respective trend line linear equations for t_c, t_f and t_m

In this study, we ensured that the dry sandy soil samples were at 0 % moisture content. This was to avoid errors due to water movement during heating. The values of temperature with time through the soil samples were obtained under transient heat flow conditions to avoid tedious measurement cycles associated with using steady state heat flow method. The steady state heat flow method generally requires a longer testing time. So, if there is moisture in soil, water may tend to migrate under the action of temperature gradient, leading to evaporation and variation of uniform water content during measurement [16]. As a result of this, we consider the steady heat flow method to be unsuitable for soil with high degree of moisture content. On the other hand, the transient heat flow method is rapid and only small temperature increment occurs in the process of test that requires a short time for a measurement cycle. Hence, even under the conditions of soil moisture, the soil water remains constant when measurements are being made.

With the current study on dry soil samples at 0 % moisture content, the effect of low heating power of 18.05 Wm^{-1} did not bring about measurement variability due to low temperature resolution. Since the heating power is not high and the sandy soil samples were in their dry state, excessive vapour transport associated with high heating power which may lead to inaccurate thermal conductivity was avoided.

5.0 CONCLUSION

Functional electrical heating equipment has been designed and fabricated for use in this study to determine heat transfer properties of dry coarse sand, dry fine-medium sand and MgO powder. It was found that the thermal conductivities of the samples were 0.21 $Wm^{-1}K^{-1}$ at 13.4 °C for dry fine-medium sand, 0.22 $Wm^{-1}K^{-1}$ at 12.7 °C for dry coarse sand and 0.36 $Wm^{-1}K^{-1}$ at 7.4 °C MgO powder. From the results of findings in this study, it can be concluded that dry fine-medium sand (0.125-0.50 mm) and dry coarse sand (0.50-1.00 mm) could serve as good electrical insulators and as good thermal conductors in electrical heating devices, such as kettles, electric irons and electric immersion water heaters with high economic importance over the conventional heaters made with MgO powder as insulator. The values of thermal conductivities of dry sand samples obtained in this study were also within the range of existing experimental results.

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